HIGH-FREQUENCY
INDUCTION HEATING

High-Frequency Induction Heating

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PREFACE

The purpose of this book is to offer the user of high-frequency induction-heating equipment basic technical application details that will serve as a ready reference in connection with the heating of metal parts, such as may be required for hardening, heat-treating, brazing, soldering, annealing, stress-relieving, forging, upsetting, or melting. Though the generation of high-frequency current is an electrical function, putting this current to practical use becomes almost entirely mechanical. It is with this that the user of induction-heating equipment is more concerned. Therefore, other than brief references to electrical data characteristic to this type of heating, the text is confined to application technique.

High-frequency heating has already demonstrated remarkable versatility in many industries and without doubt will exert a marked influence on future product design and manufacturing process-planning. Heating methods have always undergone a transition of one kind or another, and it is logical to assume that induction-heating principles will open an important field of possibilities in economies and production gains.

The text includes a broad coverage of heating coils and fixtures as used in hardening and joining operations, since these constitute the main requirements of a successful application. References are made to product design because technically there are advantages in considering the fundamental needs of induction heating when constructional details of a component are originated. In view of the association so often made between induction heating and dielectric heating, a brief chapter has been included on the latter, mainly for the purpose of showing the differences between these two methods of heat transfer.

This textbook would not have been possible without the generous assistance of manufacturers and users of high-frequency equipment who have contributed illustrations showing induction-heating installations in use. The author takes this opportunity to thank the following manufacturers for their valuable assist-

ance: Ajax Electrothermic Corporation; Ecco High Frequency Corporation; Federal Telephone & Radio Corporation; Girdler Corporation; Induction Heating Corporation; Tocco Division, The Ohio Crankshaft Company; Radio Corporation of America; Van Norman Company; and Westinghouse Electric & Manufacturing Company. He thanks also Glen C. Riegel, of the Caterpillar Tractor Company, and Richard F. Harvey, of the Brown & Sharpe Manufacturing Company. Deep appreciation is also extended to the Induction Heating Corporation for its help in making available many case histories and laboratory analyses of induction-heating problems.

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HIGH-FREQUENCY INDUCTION HEATING

CHAPTER I

PRINCIPLES OF·INDUCTION HEATING

Induction heating is a means of raising the temperature of metallic parts by the transfer of electrical energy from a high-frequency current-carrying conductor, usually referred to as a heating coil. This coil sets up a field of magnetic flux that energizes the metal workpiece in such a way that current is caused to flow around its surface. The resistance of the work to this flow, or its inability to carry the induced current, causes an immediate heating action to take place.

High-frequency induction heating dates back many years. One of the earliest uses of this source of power was in the melting of metals. For some time, however, its use for other purposes was retarded, largely because the generators required to produce high-frequency current were not commercially available. Within the past few years, however, this obstacle has been overcome and the induction heating of metal parts has advanced rapidly. Today various types and sizes of generators covering a broad field of induction-heating applications are available.

As in any other process, induction heating has its field of applications as well as its limitations. Primarily it is used for localized heating, or zonal hardening of metal surfaces. It cannot be considered a basic substitute for other specific types of heating, but rather a selective means of applying heat to parts that lend themselves to this type of process. A full knowledge of the limiting factors should be analyzed by anyone contemplating the use of induction-heating equipment.

If a machine spindle, like that shown in Fig. 1, requires hardening all over, it does not fall logically into the field of induction heating. If, however, the specifications call for

hardening all over because no other method of heat-treatment is available, but if only two or three localized surfaces actually require being hard, then high-frequency induction heating would appear as a practical means of heat treatment. The surfaces, indicated by arrows, could be selectively hardened and, since heat is limited to the surface of a small area at one time, the part would not become warped or be subjected.to metallurgical changes, and many of the economies of high-frequency induction heating would be gained.
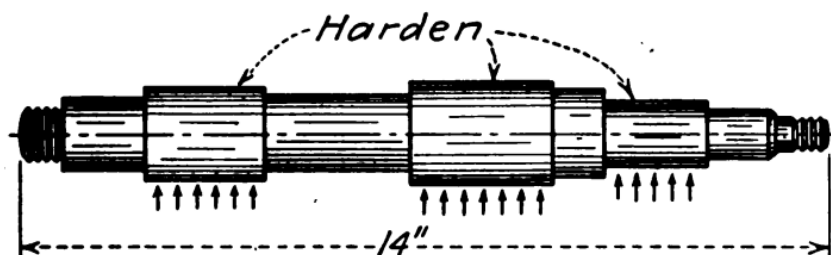
FIG. 1.—Parts requiring hardening all over usually are not suited to high-frequency induction heat-treatment. However, if only selected areas require hardening, as indicated by the arrows, then induction heating can be considered practical.

Induction-heating Field. Induction heating as applied to industrial operations, such as soldering, brazing, hardening, heat-treating, forging, and other forms of heat transfer, has so many practical applications that it cannot be overlooked by metalworking plants in search of new economies in manufacturing methods and improvements in the quality of their products. Already this art has developed to a point where operations hitherto impossible, or in which former methods proved difficult or inadequate, are being easily performed.

Many advantages have resulted from the broad experience gained through the diversified applications of induction heating. Outstanding are (1) a comparatively low heat cost, especially in cases where only a localized surface requires heating as compared with an entire component in the past; (2) the application of heat at an exceptionally fast rate, which naturally increases output; and (3) uniformity for any given quantity of parts, with a reduction or elimination of spoilage.

Linked with these three economies are many other indirect advantages such as less deformation of heated parts, often making straightening unnecessary; the hardening of surfaces without the formation of scale, thus eliminating cleaning oper-

ations; the substitution of a higher carbon steel as a means of eliminating carburizing; the use of plain carbon steels in place of the more expensive alloys; better bonds and stronger joints in brazing and joining applications; and the use of lower melting brazing alloys in place of those requiring high temperatures and a controlled atmosphere.

Basic Principles. Since induction heating is a process by which the temperature of a metal part is raised by the electrical generation of heat within the material, the part being heated is in no way a part of any closed electrical circuit. To generate heat to a given part therefore requires a current-carrying conductor, usually referred to as the heating coil, as illustrated in Fig. 2, which is made to surround the surface to be heated. The high-frequency current enters at one terminal and passes around the coil and out of the other terminal, as indicated by the arrows. This current sets up a field of magnetic flux, which flows around the surface of the work in the opposite direction. Magnetic fields occur in the area surrounding the heating coil, their strength varying inversely as the square of the distance from the surface of the work. What takes place is a transfer of electrical energy from the coil into the material, whence it is converted into heat. For maximum heating, therefore, the current-carrying coil should be arranged close to the work, the average coupling being from $\frac{3}{32}$ to $\frac{3}{16}$ in. when fast heating is desired, and increased proportionately for slower heating.

In heating metallic parts by means of inductive currents, it is necessary to take into account (1) the output power of the generator; (2) the frequency of the power supply; (3) the design or shape of the heating coil and its relation to the surface of the work, and (4) the resistivity of the metal being heated.
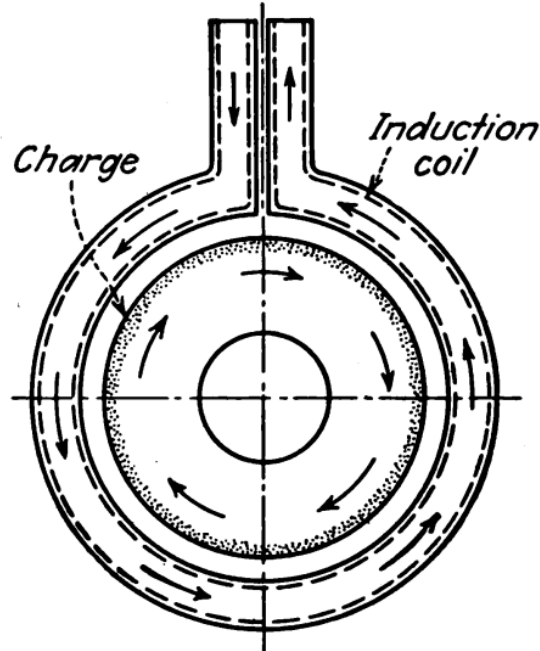

FIG. 2.—Induction heating is the result of the transfer of high-frequency current from a coil to the workpiece. The resistance of the work to carry the induced current results in an immediate heating action.

To begin with, there must be enough power to heat the surface or mass of the part to be treated. A generator with an output of 20 kw. might cover a broad field, but there is a limit to the size of the part it can handle. For example, a gear blank 12 or 14 in. in diameter, with a 2- or 3-in. face, would be impractical with such a unit, because heat losses through convection and radiation would offset the heat-producing energy of the inductor; thus the outside would reach a certain temperature and go no higher. For such a part a generator of 50 to 100 kw. output would be required.

In other words, with induction heating it is desirable to heat surfaces at relatively fast rates and to use a generator with enough power to overcome excessive heat losses through conduction or radiation. While no single rule can be applied to determine the power requirements for general heating applications, because of the wide variation in shapes and often because of certain coil limitations, a general guide is to provide about 2 kw. output for each square inch of surface to be heated. This rate will vary with the size and shape of the part being heated but will serve as a reference to keep from going too far astray.

The energy required to heat a given part is expressed by

$$W \times S \times T = \text{B.t.u./min.},$$

where W = the weight of material,
S = the coefficient of specific heat of the material, and
T = the temperature rise required.

This formula does not allow for normal heat losses, which may run from 25 to more than 50 per cent, but by comparing the approximate power needed with the available power of a generator, it is possible to determine quickly if the equipment is suitable.

More detailed data on power calculations are given in other chapters. The coefficient of specific heat of a material is the number of B.t.u. required to raise 1 lb. of that material 1°F. Water is assigned as a standard and is given a specific heat of 1.0, so that it takes 1 B.t.u. to raise 1 lb. of water 1°F.

Relation of Frequency. Of great importance is the frequency of the power source, which of course has a direct influence on the depth of heat penetration. The higher the frequency, up to
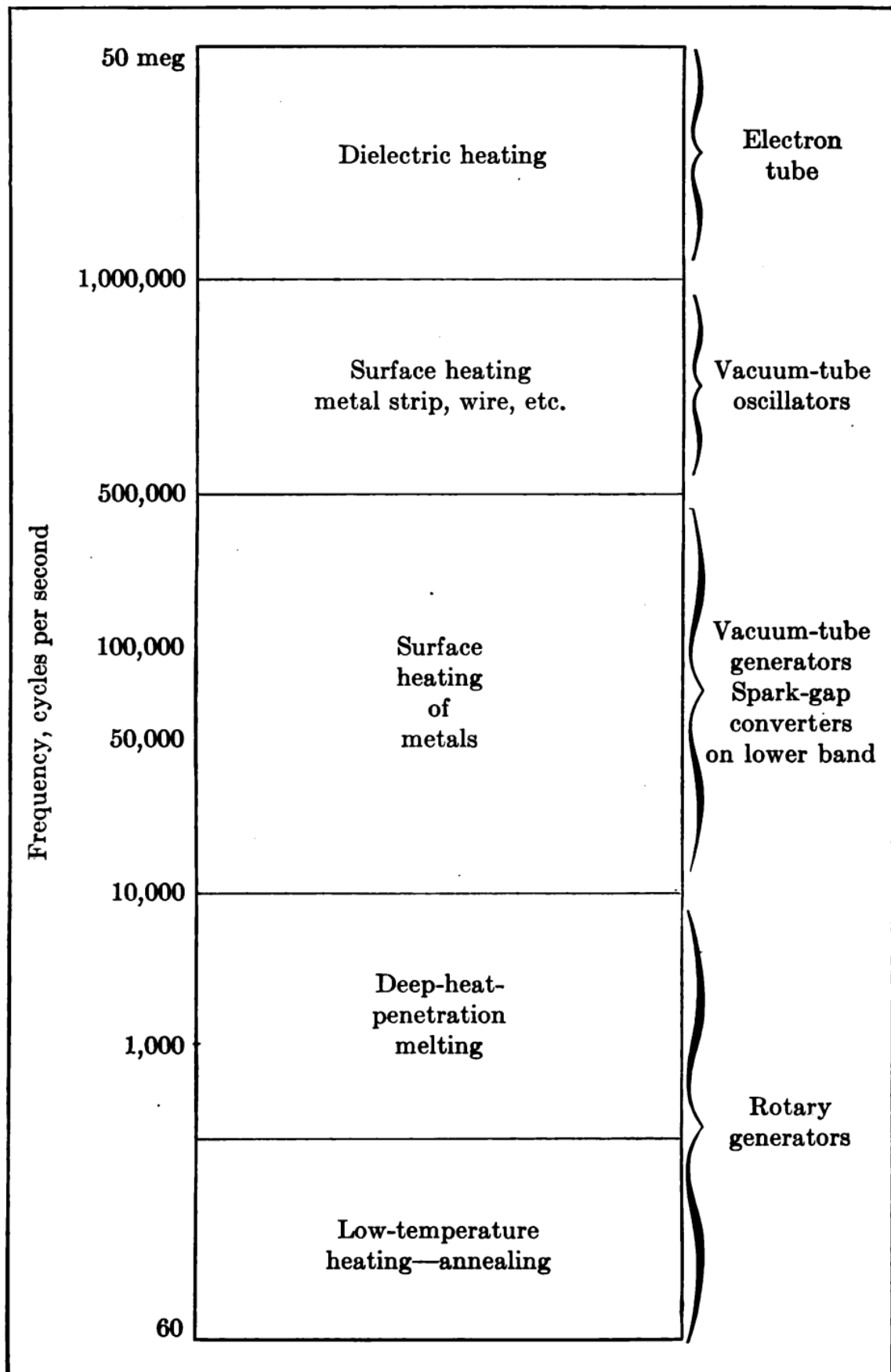
FIG. 3.—Induction heating of metal parts is carried out at various frequencies. Most surface heating operations are performed at frequencies of from 10,000 to 500,000 c.p.s.

a certain range, the more pronounced the surface heating effect. A frequency of 2,000 cycles per second may heat a surface to a depth of ⅛ in., whereas a frequency of 200,000 c.p.s. will produce a much shallower heat zone, on the order of 0.020 in. depth.

The speed at which a part can be heated and the depth of the heated layer are determined by the power output and the frequency of the generator. With proportionate power available, the speed at which heat may be applied can be made practically the same over a wide range of frequencies. However, there usually is a frequency best suited for the average range of work and, likewise, a generator which serves that range to best advantage. The problem therefore usually resolves itself to the matter of using available equipment to cover as broad a field as possible, rather than attempting to match a generator for each specific job.

For the heating of parts where a deep penetration is desired, frequencies of 2,000 to 10,000 c.p.s. usually are applied. Where only surface heating is required, a frequency range of 200,000 to 500,000 c.p.s., usually referred to as 200 to 500 kilocycles, is preferable and, as a rule, will cover most of the parts to which induction heating can be applied. For extremely thin heat layers, frequencies of 1 megacycle or more may be used. One kilocycle equals 1,000 cycles, and 1 megacycle equals 1,000,000 c.p.s.

A chart showing the frequencies used for high-frequency heating is illustrated in Fig. 3. The lower range of frequencies is produced by motor-generator sets, and the higher range mostly by vacuum-tube generators. High-frequency heating has two distinct fields—induction heating for metals and dielectric heating for nonmetallic materials—and it will be seen on this chart that the upper range, up to 50 or more megacycles, is for nonmetallic materials, such as wood, plastics, rubber, and ceramics.

With induction heating, a heating coil or inductor is made to surround the surface to be heated, as illustrated at the left in Fig. 4, whereas with dielectric heating the charge is placed between two electrodes through which the high-frequency current passes to produce internal heat, as shown at the right. The equipment used for these two types of heat is somewhat similar in design and principle, but the induction generator is suited only to metals and will not heat dielectrics which require a much higher frequency and voltage across the electrodes. Likewise, a

dielectric generator cannot be used for metallic parts, because of the voltage breakdown that would occur. A brief outline of the principles involved in dielectric heating is covered in another chapter.

Resistance is the property of an electrical circuit which determines the rate at which electrical energy is converted into heat in relation to a given amount of current. The term is applied when the rate of conversion is proportional to the square of the current, in which case it is equal to the power conversion divided by the square of the current.
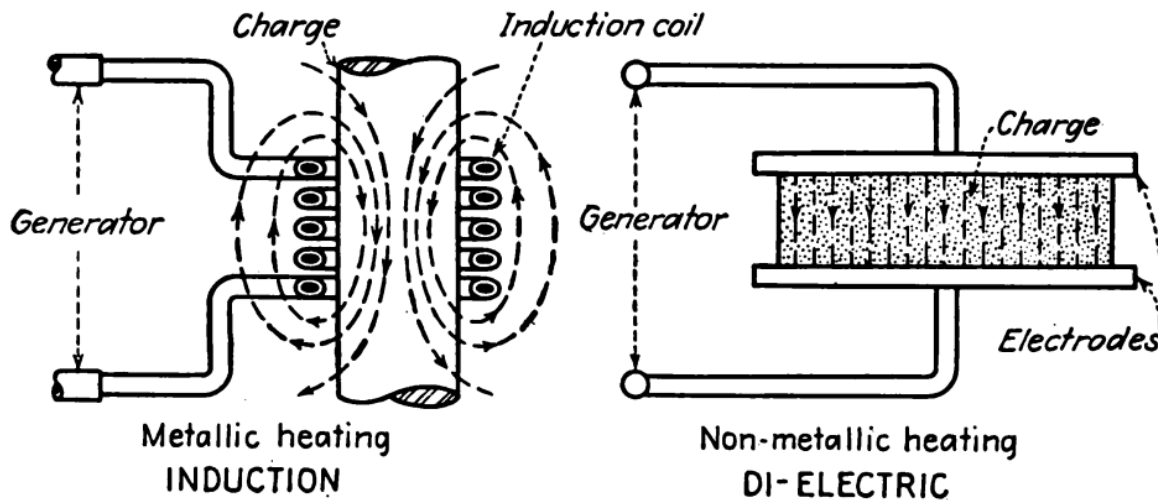
Fig. 4.—Comparison between induction and dielectric heating. Induction heating is confined to metallic parts, whereas dielectric heating is used almost exclusively for nonmetallic materials.

The power-output rating of a high-frequency generator is based on the formula for determining the heat it will produce in a given mass to increase its temperature a specific number of degrees Fahrenheit, or

$$\text{kw.} = 2.93 \times \text{wt. of mass} \times \text{sp. heat} \times \text{temp. rise} \times 10^{-4}$$

Electrical meters and measuring devices are available for determining the power and output of generators, such as an indicating kilowatt meter. If a check is wanted for reference where these are not available, a heating tank may be used, as illustrated in Fig. 5. As water passes through the tank, it is heated by the coil *A*, which surrounds it. Thermometers are placed at the inlet and outlet connections, and the differential in temperature for a given amount of water is calculated in B.t.u. or

$$8.33 \times \text{gal. per min.} \times \text{temp. rise} = \text{B.t.u./min.}$$

Graduated-flow meters with linear calibrations, employing a glass tube and a metering float, are often used for measuring the flow of water. The size of the heating tank and the type of coil used for heating may vary somewhat according to the characteristics of the generator, but the resulting calculations will give a fairly accurate rating of the actual output power produced.

Transfer of Heat. Induction heating is based on established electrical formulas and to a great extent follows transformer principles. Linked with the electrical producing energy is the consideration of heat flow in metallic bodies. With a certain
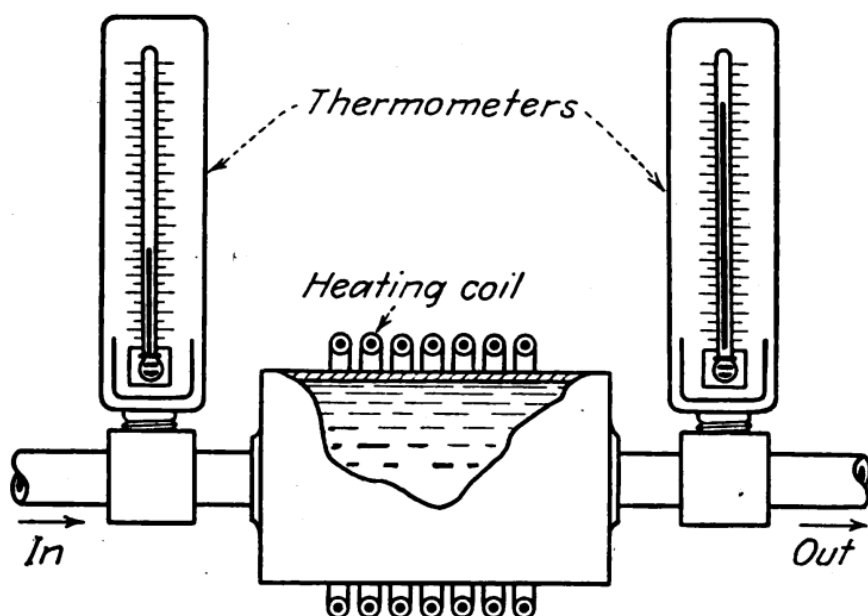
Fig. 5.—The power output of an induction-heating generator can be measured by checking the temperature rise of a given amount of water as it passes a heating tank surrounded by a coil.

amount of current induced into a workpiece which requires heating, the rate of absorption is determined by the nature of the work to absorb it. Magnetic materials heat more quickly than nonferrous metals; therefore the heating rate varies with the coefficient of specific heat of the material. The relation of the heating coil, or current-carrying conductor, and the workpiece to each other determines the amount of heat transfer in proportion to the power supply.

The heating coil theoretically becomes the primary and the workpiece the secondary, and, as in a transformer, the closer the coil to the work's surface the more intense the transfer of magnetic flux. This is illustrated diagrammatically in Fig. 6,

showing a multiturn coil surrounding a steel bar or shaft, requiring heating at its center section.

Since high-frequency heating of a metal part is the result of generating magnetic flux to the work's outer surface, which
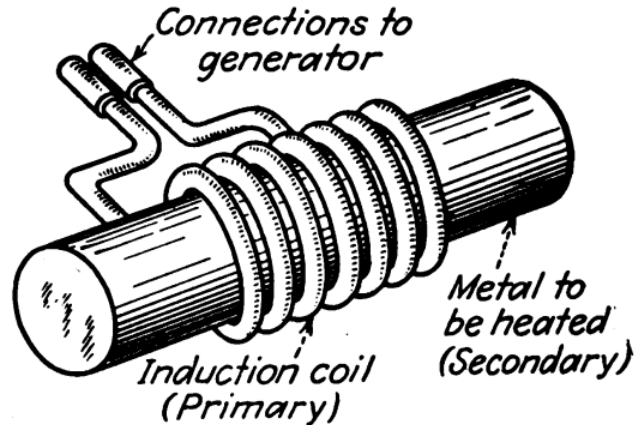
FIG. 6.—Induction heating is based on Ohm's law, transformer principles, and rules governing the flow of heat in metals. Theoretically the heating coils become the primary and the workpiece to be heated the secondary.

decreases in intensity toward the center, it is possible with proper timing to control the depth of heat so that, for operations such as surface hardening, a predetermined case can be obtained. In
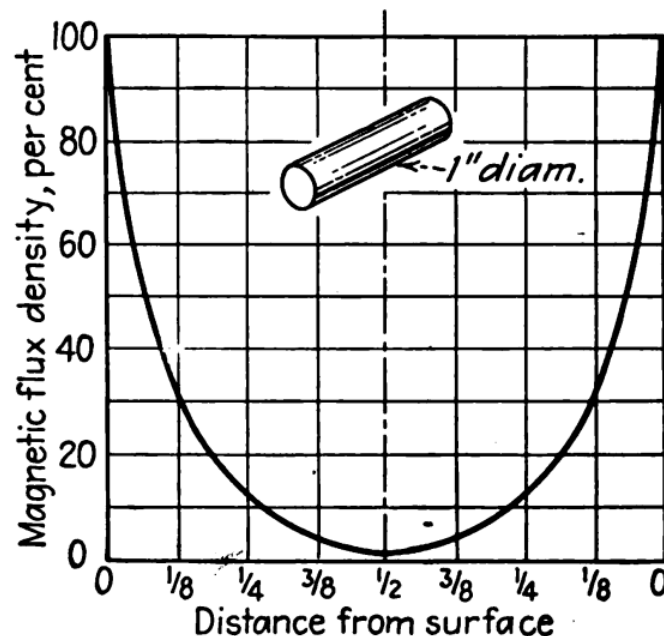
FIG. 7.—When a metal part is heated by high-frequency current, most of the heating is localized at the surface. The higher the frequency, the more pronounced the surface-heating effect.

Fig. 7 is shown a chart representing the gradient of magnetic flux, when heating a 1-in.-diameter shaft by means of a generator having a frequency of between 300 and 400 kc. The greatest

part of the heat generated is on the surface, diminishing rapidly toward the center, where practically no heat is attained. At a distance ⅛ in. below the surface, only about 25 per cent of the flux density is noted, whereas for approximately ⅓₂ in. depth at the surface more than 80 per cent of the total heat is concentrated.

This curve will vary somewhat with a change of frequency. Using a lower frequency of 9,600 c.p.s., the depth of the heated
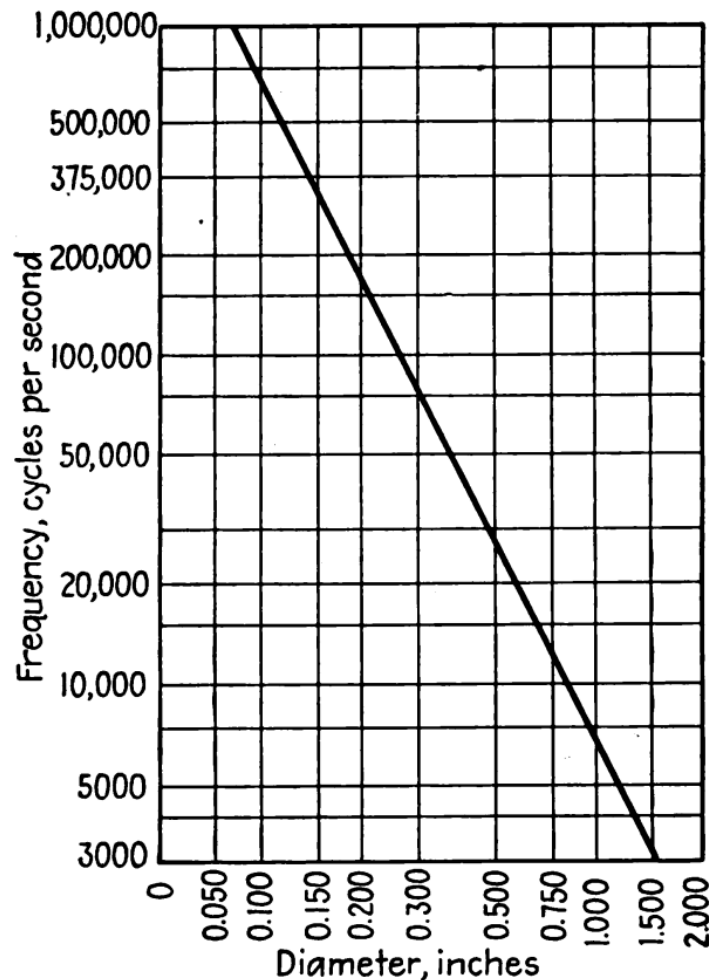
FIG. 8.—This chart shows the theoretical relationship between the diameter of small steel rods and wire, and the minimum optimum frequency which should be considered when hardening temperatures are desired.

area would be more nearly ⅛ in., and with a much higher frequency the penetration would be around 0.010 in. These references are given merely to show the relative effect of frequency. The depth of the heated area can be increased, of course, by added heating time, if sufficient power is available.

When small steel rods and wires are to be heated by high-frequency current, the relationship betweeen the diameter and the minimum optimum frequency becomes more critical. Where

hardening temperatures of 1450 to 1500°F. are required, the smaller the diameter the higher the minimum frequency, as shown in the chart in Fig. 8, which represents minimum optimum frequencies appropriate for steel wires, rods, or bars of different diameters. However, the use of frequencies higher than those shown, particularly for the larger sizes, is entirely practical, especially for surface-heating requirements. While theoretical calculations would show that a ⅛-in.-diameter wire could be surface-heated at a frequency of about 500,000 c.p.s., allowances usually are overlooked for the rapid flow of heat by conduction below the surface. Usually small diameters heat through almost instantly, and surface-heating of such small sizes becomes impractical. The formula used for obtaining the frequency for such parts is

$$F = 1.22 \, \frac{\text{resistivity (ohms-centimeters)}}{(\text{radius of rod})^2} \times 10^7$$

For nonferrous wires and rods of small diameters, a much greater frequency is required.

With all heating coils there are alternating magnetic lines of force which are perpendicular to the path of the current and which, in turn, follow a direction determined by the flow of current in the coil. This magnetic field surrounding the coil, as illustrated in Fig. 9, representing both single- and multiturn coils, produces internal energy losses in the material located within the coil, causing rapid temperature rises.

Induction Heating Coils. Current-carrying conductors for induction-heating purposes are invariably made of copper. The conductivity of the copper should be high, at least 90 per cent or better. To be a good conductor, the material must afford a continuous passage of electrical current, even when subjected to a difference of electrical potential. The greater the density of current for a given potential, the more effective the conductor.

The conductivity of copper is calculated by dividing the resistivity of the international annealed copper standard at 20°C. by the resistivity of the sample at 20°C. Either mass resistivity or volume resistivity may be used.

Usually the copper used for standard tubing, bars, sheets, and flats will make good heating coils for induction purposes. When special cast-type coils are made, however, the material specifi-

cations should be carefully checked, because a copper containing alloys, which will lower its conductivity, will detract from the

Pattern of magnetic flux

Multi-turn coil

Single-turn coil
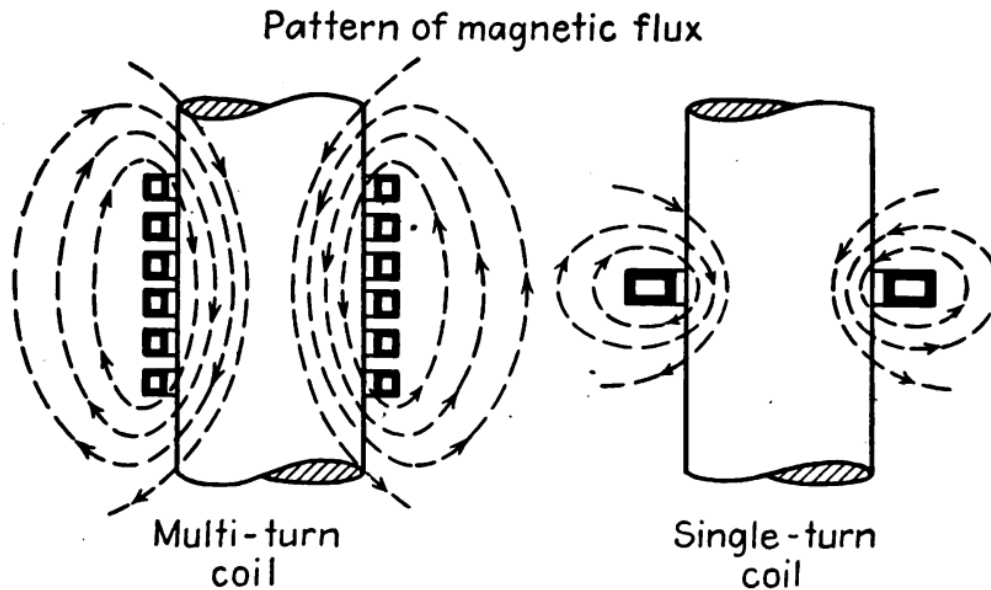
FIG. 9.—An induction-heating coil when energized sets up a magnetic flux that surrounds the coil as shown, whether it is of the single- or multiturn type. The density of the flux is greater within the coil than at the outside.

heating efficiency of the coil. See the table of specific heats for comparative conductance values of various materials, shown in Fig. 10.

Material	Coefficient of specific heat	Relative conductance, per cent	Specific resistivity
Aluminum	0.210	63	2.8
Brass	0.090	27	7
Copper	0.091	100	1.72
Iron	0.108	17	10
Lead	0.031	8	22
Nickel	0.118	22	7.1
Platinum	0.031	17	10.2
Silver	0.063	106	1.62
Steel	0.148	14	10 to 15
Tin	0.057	15	11.9
Tungsten	0.032	32	5.7

FIG. 10.—Inductors for high-frequency heating should be made of copper having a high conductivity. The rate at which metals can be heated depends on the coefficient of specific heat.

Heat-producing losses are those internal energy losses which cause a temperature rise in the material linked by the magnetic

lines of force. In magnetic material these are divided into two classes—hysteresis losses and eddy-current losses, as shown in the chart in Fig. 11. According to popular conception of atomic structure, hysteresis losses are caused by the friction of adjacent molecules in a given material, when these molecules are caused to vibrate in an attempt to align themselves to the frequency of the magnetic field. This loss is peculiar to magnetic materials, and its probable cause is that molecules of magnetic materials are in themselves small magnets vibrating at the same frequency as the alternating magnetic field linking this material. Hence, a
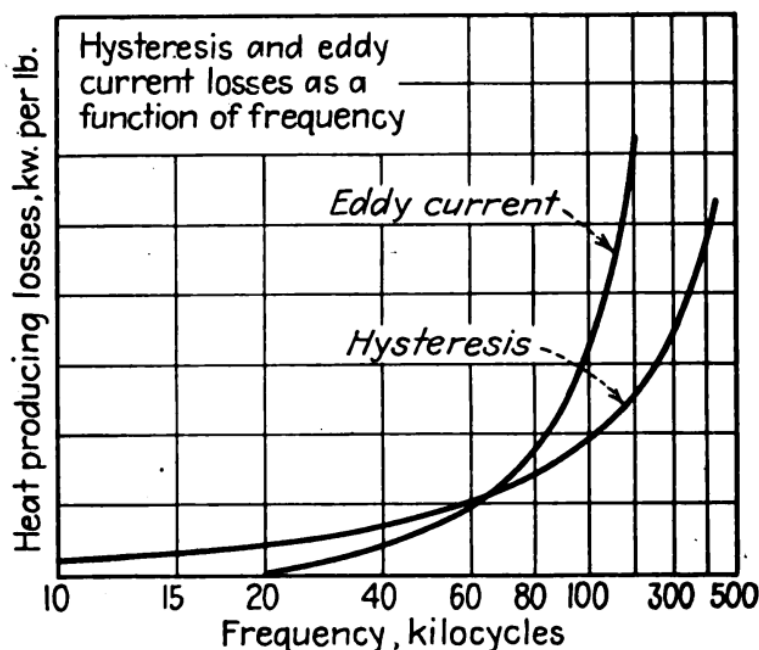
FIG. 11.—In heating magnetic materials, heat-producing losses are divided into two classes: hysteresis and eddy-current losses. In nonmagnetic materials, only eddy-current losses are present.

certain amount of heat energy is generated and this heat, commonly termed the hysteresis loss, is directly proportional to the frequency of the magnetic field causing the vibration and the magnetic-field strength.

Eddy-current losses are resistance losses resulting from small circulating currents within the material. These currents are caused to flow by virtue of differences in potential at various points in the material, these differences in potential being caused by the alternating magnetic field cutting the work. The loss is proportional to the square of the current flowing and also directly proportional to the electrical resistance of the material. Hence, it can be considered to be proportional to the square of the fre-

quency and field strength, since the potential difference and the resultant currents vary with this relation. In nonmagnetic material, eddy-current losses are the only losses present; hence, any induced heating must be accomplished through this source only.

In surface-heating a steel part by high-frequency current, the permeability of the material increases with temperature rise up to the critical point, where magnetic properties no longer exist,
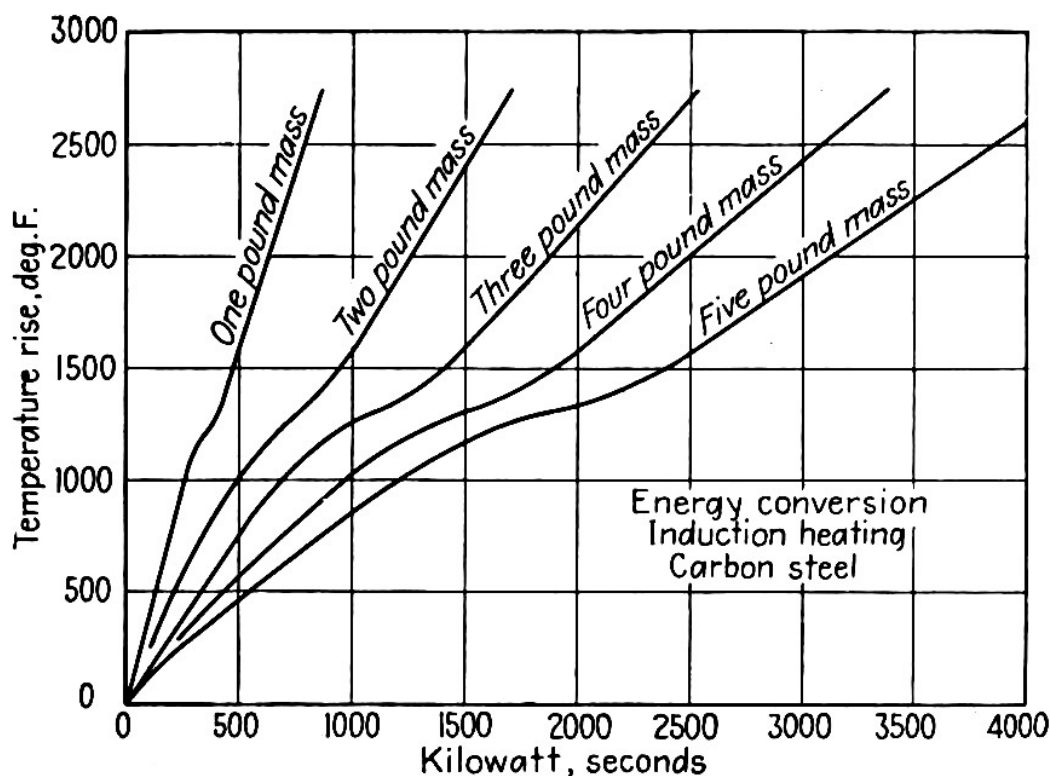
Fig. 12.—When a steel part is inductively heated, the temperature rise is constant up to the critical point, at which temperature the rate of heating is somewhat reduced.

about 1450°F. Above that point, the permeability is equal to unity and the power absorbed at the surface of the workpiece diminishes.

A graph showing energy conversion for inductively heating carbon steel is shown in Fig. 12. These curves represent different loads of from 1 to 5 lb., using a 15-kw. generator. The energy required for heating these loads is somewhat proportional throughout the temperature range. The variation in the curves, at about 1450°F., represents the critical temperature where hysteresis losses cease as a function of heating, and at which point the rate of heating is slower.

The effect of surface-heating by means of an induction coil is illustrated in Fig. 13. The dark area represents the surface layer, which receives the maximum flux density and, consequently, the most heat. If the current continues to flow, heat is generated to the next theoretical subsurface layer, because the current density travels inward, and the thickness of the heated zone likewise increases. The outside surface temperature, however, does not increase proportionally to the inner layers—an advantage in that surface overheating does not take place immediately, even though the predominating heat is at the surface.
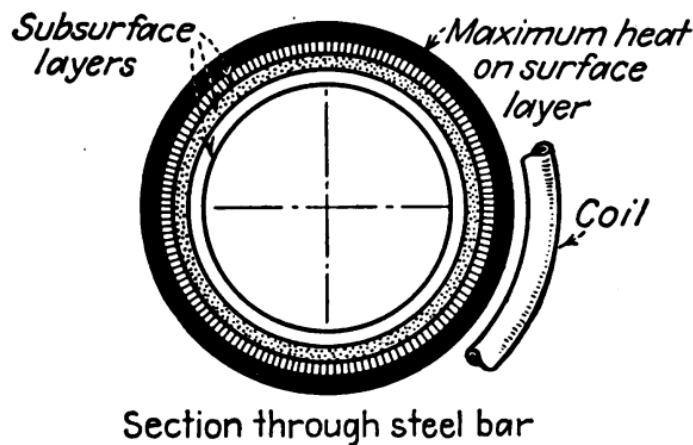
Section through steel bar

FIG. 13.—In theory, high-frequency heating is produced on the surface of a workpiece in layers. The longer the duration of the heating cycle, the deeper the penetration of heat.

Continuing the application of high-frequency current, however, will result finally in additional layers becoming heated, until the entire cross-sectional area of the piece is heated through, provided the generator has sufficient power for this purpose. From here on the surface will begin to overheat and finally reach a melting temperature.

In high-frequency surface hardening, however, the purpose is to heat the surface only to a predetermined depth and then apply a suitable quench, so that overheating usually does not take place because of the large unheated mass lying directly under the heated zone. Applying flame heating to a similar piece, the temperature rise is more constant during the heating period and there is a tendency to overheat the surface. This comparison is made merely to emphasize the advantage of inductive heating, where power absorption diminishes above the critical point, usually eliminating overheating, over other methods where such

a heat control does not exist and burning of the surface is more likely to occur. Then, too, with high-frequency heating, the heat-producing current can be stopped at will, so that overheating can be easily controlled.

Inasmuch as localized surfaces can thus be heated rapidly by means of high-frequency induction current, new methods of manufacture and basic changes in product design are possible in this heating process as representatively shown by the example in Fig. 14. All these methods include modifications from normal
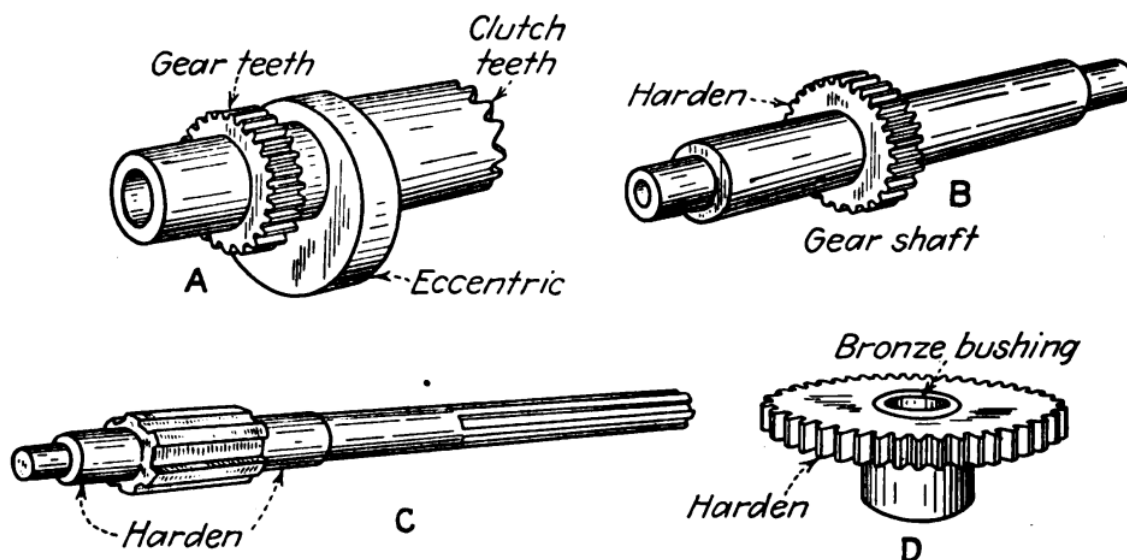

Fig. 14.—A representative group of steel parts illustrating some of the advantages of high-frequency induction hardening. Only localized surfaces are treated, so that scale and deformation are reduced or eliminated.

procedures, which are but a few of the changes resulting from this process of heating. At *A* is shown a machine part in which three surfaces require hardening in different degrees. Normally it would be difficult to produce such a part, but with high frequency the undertaking is relatively easy. Each surface is heated separately, as an individual cycle. The eccentric or cam requires maximum hardness, since it operates a plunger and therefore is hardened to 62 Rockwell C. The gear teeth, because of their duty, need not be so hard and are treated to 56 to 58 Rockwell C. The clutch teeth, on the other hand, which are subjected to impact only are hardened to 50 to 52 Rockwell C. Many other machine parts requiring variations in hardness can be easily produced by the induction method.

At *B* is shown a long shaft on which a spur gear is integrally machined, and on which only the teeth require hardening. Here,

again, the normal procedure would be to subject the entire piece to heat, from which would result some deformation, requiring a straightening operation, and also the formation of scale, necessitating cleaning. With induction hardening, however, the gear teeth can be hardened individually without affecting the ductility of the remainder of the part, with an appreciable saving in manufacturing cost. The shaft at *C* is heat-treated and machined as shown, but requires two hardened bearings, as indicated, one on each side of the short spline, on which needle bearings operate. Here, again, the normal procedure would be to heat the entire end of the shaft and quench it, which most likely would result in deformation and a difficult straightening operation. By the induction method, the journals can be individually hardened without metallurgically affecting the adjacent portion of the shaft.

Frequently gears are hardened and fitted with sleeves or bushings, necessitating grinding of the hole by means of locating from the pitch diameter of the teeth, as in the example shown at *D*. This is done to assure concentricity, but there is of course a chance also of certain misalignment. By means of high-frequency heating, however, it is possible to press the bushing into the gear blank before the teeth are cut, then cut the teeth from the bushing so that concentricity is assured. The final operation is the induction hardening of the teeth, which on a gear of this type can be carried out with practically no deformation whatever, and without the formation of usual scale.

Types of Coils. Heating coils for high-frequency induction heating can be made in a wide variety of styles and shapes, depending upon the nature of the operation. To some extent the design of a coil will be limited to certain types of generators. In Fig. 15 a few of the more commonly used coils are illustrated. The most used general-purpose type is perhaps the one shown at *A*, which is wound or formed from copper tubing either symmetrical in contour or formed to suit the shape of the part as shown at *B*. Solid-type inductor coils, like the one shown at *C*, are also widely used and are particularly suitable for heating parts requiring a restricted zone. The coil shown at *D* is of series design, which makes possible the heating of several pieces at one time. The coil at *E* is made of flat strip, which, as may be seen, can be used in a variety of heating operations.

Regardless of the type of coil used, it is necessary to provide cooling. In the case of the multiturn coil this is accomplished by circulating the water through the coil itself, whereas with the single-turn inductors a cooling tube is added to the outside or other suitable internal cavities are provided for the passage of water.

A symmetrical heating coil can be used for a part with an irregular surface, provided, of course, that the outer surface or contour is not too irregular or pronounced in shape.
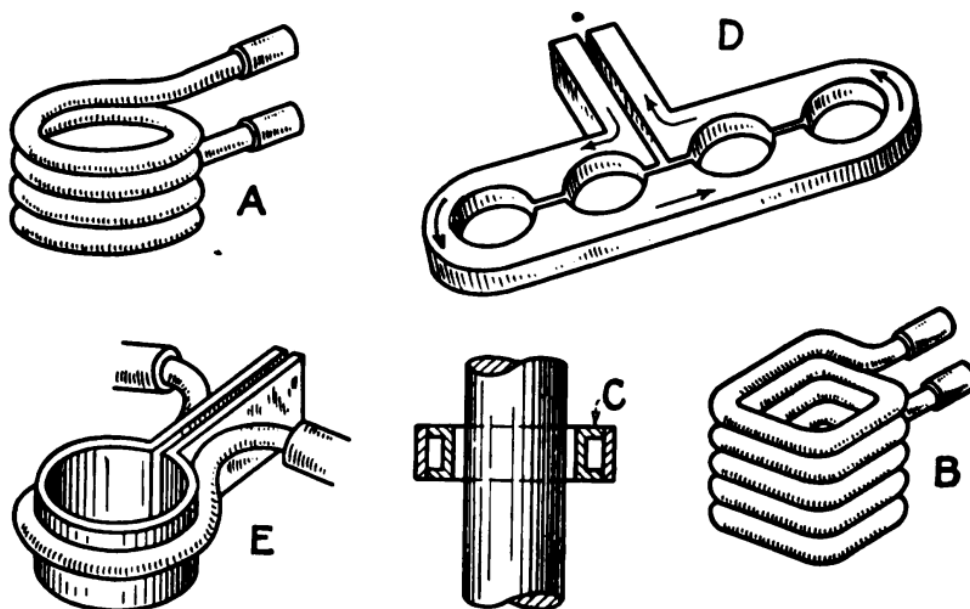

FIG. 15.—High frequency induction-heating coils can be made in a wide variety of styles and shapes. The most common are multiturn coils made of copper tubing, and single-turn coils made of flat bars, strips, or tubing.

Since high-frequency current has a tendency to follow the outer surface of a piece placed within a coil, the irregular part shown in the circular coil at the left in Fig. 16 will be heated fairly uniformly around its periphery even though its contour is irregular, resulting in a variation in coil coupling. If, however, the contour of a certain part is especially pronounced, as shown at the right, it is advisable to provide a heating coil which conforms to the approximate shape of the part, as illustrated.

This principle is shown again in Fig. 17, representing coils for heating hexagon nuts. With the small nut shown at the right, the variation in surface is not too pronounced and a symmetrical coil may be used advantageously. With the much larger nut shown at the left, however, there is more of a variation in the coupling, and if a symmetrical coil were used there would be a

tendency to produce more heat at the corners of the nut than at the flats. As will be seen, therefore, the coil for this part is of hexagonal shape, which ensures a more even distribution of heat to the entire outer surface of the nut.
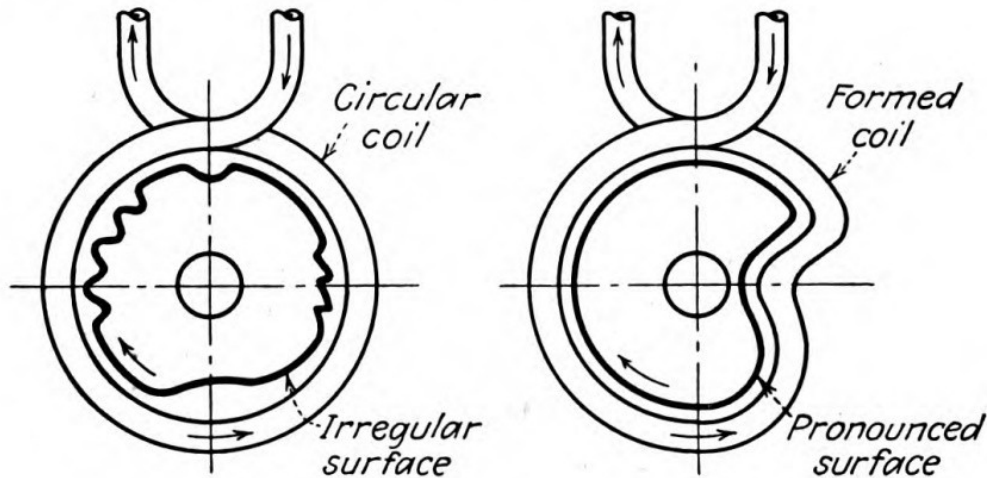

FIG. 16.—Irregular surfaces in which the variation of contour does not exceed about one-tenth of the diameter can be heated with a cylindrical coil. Where a pronounced irregularity exists, however, the heating coil should conform to the contour of the surface to be heated.
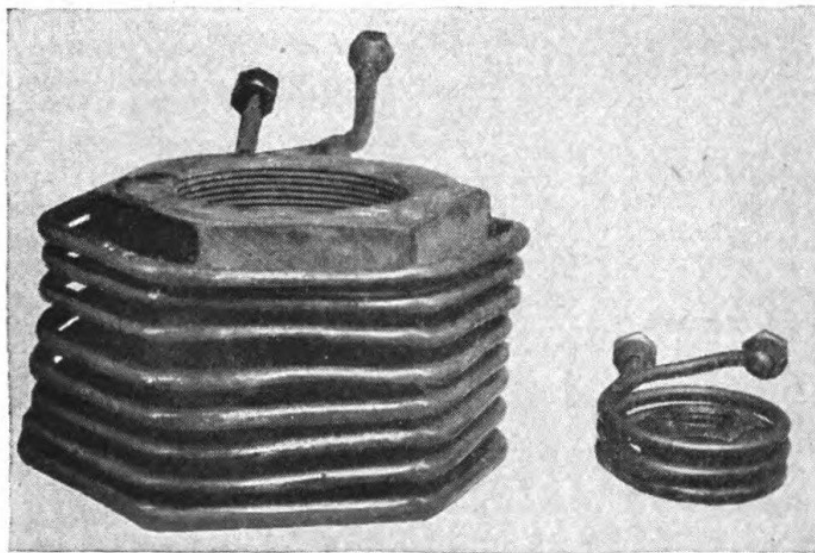
FIG. 17.—Representative heating coils for large and small hexagon nuts. A formed coil, conforming to the shape of the nut, is required for the larger size to insure uniform heating.

This heating condition, however, will vary with the height of the coil in relation to contour of the work. With a wide coil, where the work is off center, a more uniform heat may be expected around the surface of the work than with a narrow coil under the same conditions. This shows that with narrow coils the need of a uniform coupling is more imperative than with wider coils.

Where such a variation exists, owing to the shape of the work or to the impossibility of forming a coil to conform to the contour of the work's surface, the part should be rotated if possible so as to offset the one-sided heating condition.

The magnetic flux set up by the high-frequency current of the type used for heating metals will pass through dielectric materials, or particularly those of a nonmetallic nature. For example, if a heating coil is placed under a sheet of plate glass, as illustrated in Fig. 18, with a piece of steel placed directly above, the portion closest to the coil will heat as readily as if the glass were not there.
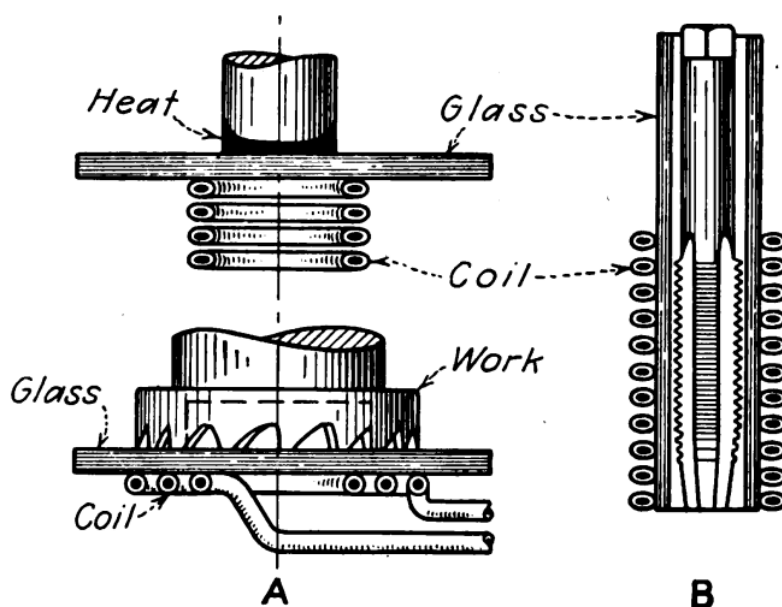

Fig. 18.—High-frequency current of the type used for the heating of metals will pass through dielectric materials, or practically all those of a nonmetallic nature, such as the glass plates and glass tube shown in this illustration.

Sometimes insulating material can be used to advantage in providing the correct spacing between the coil and the work, as indicated in the lower part of the illustration at *A*. In this case a pancake-type heating coil is placed under a piece of plate glass and the part to be heated is located on top. When the heating coil is energized, the clutch teeth will heat immediately to the desired temperature, which operation might be controlled by a timer. The same condition is true with the example at *B*, in which a glass tube is surrounded by a heating coil, and within the tube is placed the part requiring heating.

Dielectrics are widely used in connection with induction-heating applications. Sometimes the coil itself can be covered, or coated with a cement having a ceramic or porcelain base, and thus

provide insulation so that the workpiece will not come in contact with the coil.

Rules governing the selection of heating coils, whether they should be of single- or multiturn design, usually are based on the type of generator to be used and the nature of the operation to be performed. Usually the shape of the work and the area of the zone to be heated will determine the design most appropriate. A few of the basic considerations are as follows:

Single-turn coils are preferred when the heated area is narrow or restricted.

Single-turn coils are more practical where the height does not exceed the diameter.

Multiturn coils are to be preferred for heating long areas.

When the length of a coil exceeds eight times its diameter, uniform heating may become difficult.

Long areas should be heated by progressive feed through short coils.

On multiturn coils, keep the space between windings at a minimum where uniform heat is wanted.

A separate chapter dealing with the design of coils for various forms of induction-heating applications gives a more comprehensive analysis of their construction and application.

CHAPTER II

TYPES OF INDUCTION-HEATING EQUIPMENT

Induction-heating equipment for hardening, brazing, soldering, melting, forging, and other forms of heat transfer to metallic parts is made in a wide range of sizes to meet a great many heating requirements in industrial plants. These units are available at different output-power ratings, and at various frequencies, each of which covers a certain range of heating applications.

There are three basic types of equipment used for inductively heating metal parts. These are (1) the motor-generator set; (2) the spark-gap converter; and (3) the vacuum-tube or electronic-type generator. In principle they are alike in that an inductor or heating coil surrounds the work to be heated, or perhaps is formed to suit the area requiring heat, so that with a flow of current induced to the work's surface from the coil, an immediate heating action takes place. However, since the frequency of the current has a direct effect on the depth of heat penetration, one type of unit will perform some types of heating operations better than others.

Motor-generator Sets. For heat-producing current at the lower frequencies of from 2,000 to 9,600 c.p.s., motor-generator sets are available with power-output ratings of from 5 to 500 kw. At the frequencies covered by these units a deep penetration of heating takes place. These sets therefore are widely used for the heating of parts where deep hardening is required, or for the through heating of bars, such as those required for forging. When in operation, the motor-generator runs continuously, most usually at a speed of 3,600 r.p.m.

Spark-gap Converters. One of the earliest means of producing high-frequency current is by the spark-gap-type converter. Units of this type are made in sizes from 5- to 50-kw. input power range, and at operating frequencies of from 25,000 to 250,000 c.p.s. This type of set is not feasible in large-sized units and, while rated by its input power, it has an output efficiency of approximately 50 per cent, so that the power output

22

rating comparable to other units would be from $2\frac{1}{2}$ to 25 kw. In order to obtain correct operating efficiency, a series of spark gaps must be accurately adjusted. Power consumption is low during stand-by periods, as compared with the motor-generator type set.

Vacuum-tube Oscillators. The electronic-type generator, using vacuum tubes for power transmission and oscillation, has perhaps the broadest scope in the induction-heating field. Generators of this type are available in ranges from 1 to 400 kw. output power, and with frequencies of from 100,000 to 1,000,000 c.p.s., or more if desired. Their broadest use, however, is in the 5 to 50 kw. output range, at frequencies of 150,000 to 500,000 c.p.s. In operation they are silent and use little power during stand-by periods, or principally that required only for heating of the tube filaments. Maintenance requirements are exceptionally low, especially when compared with the spark-gap-type sets, which depend on gap settings for correct power transmission. The power tubes render a comparatively long service life, of 10,000 hr. or more, for average applications. Units of this type provide a constant and uniform power output throughout their tube life.

Selection of Equipment. Most induction-heating units can be used continuously for single-purpose operations and are flexible enough to permit change-overs from one operation to another. They can be set up into a production line and operated as any other machine for a single purpose, or they can be installed in a central location within a plant and arranged to handle a multitude of heating operations.

For general-purpose heating applications, it should be remembered that any one type of unit is limited to workpieces within a given size range. In other words, a generator of 10 kw. cannot handle the hardening of a large component, say for example a gear 10 in. in diameter with a 1-in. face. Such a unit would very likely be too large for delicate parts, like those required for instruments, or where a very small area may require heating, unless such parts can be handled in multiples in order to distribute the available power over a larger mass.

In attempting to surface-heat parts that are oversize for the available power of a generator, the advantages of rapid inductive heating are lost. The absorption of heat will be slow and some-

times will dissipate itself into the inner area before the desired temperature is reached on the outside surface. In other cases the proper heat eventually may be attained, but much of the energy will go deep into the surface of the part, largely by conduction, possibly resulting in excessive distortion and indicating that more power energy is needed.
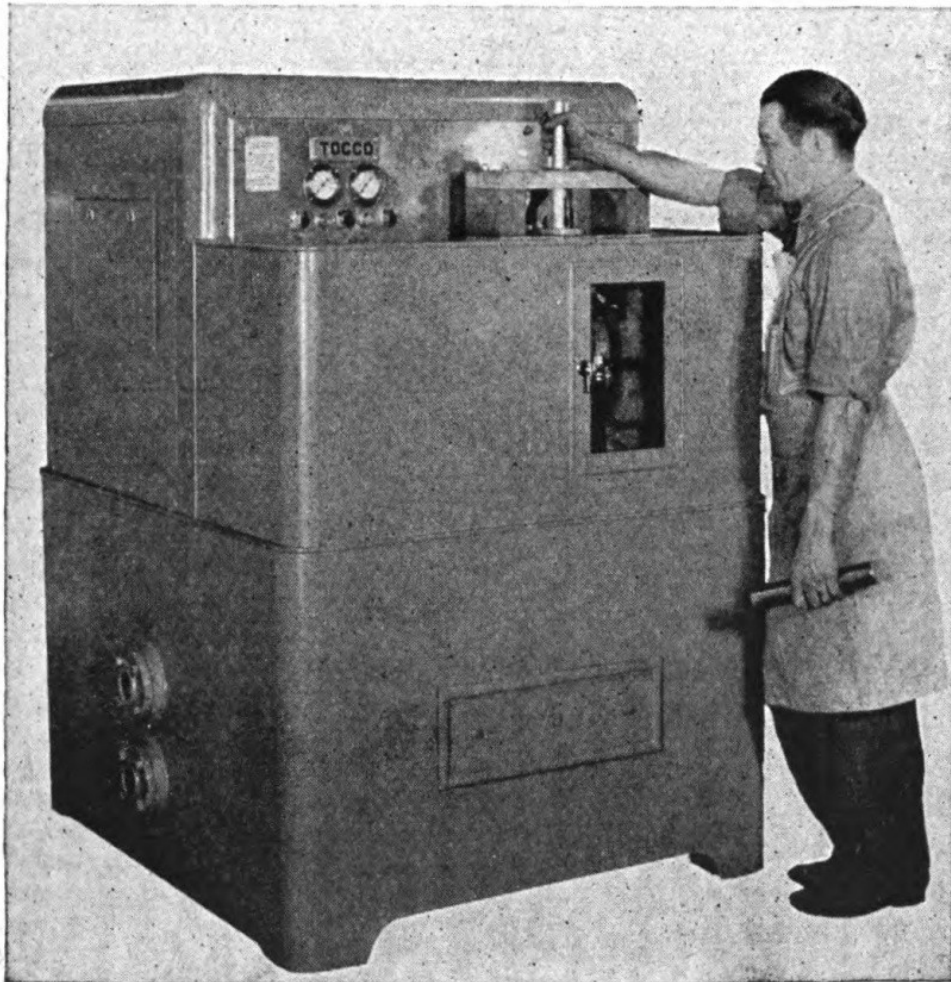

FIG. 19.—A representative type of motor-generator induction-heating unit, having a capacity of 20 kw. at 9,600 c.p.s. (*Courtesy of The Ohio Crankshaft Co.*)

The selection of induction-heating equipment, therefore, resolves itself to analysis of the mass or weight of the material to be heated and the temperature rise required, in relation to the available output power of the generator. It must also be determined whether a deep or shallow heated surface is required, which in turn governs the frequency.

If a 2-in. steel shaft requires through heating on one end for forging, a low frequency of 9,600 c.p.s. would be appropriate. If, however, a surface hardness of $\frac{1}{32}$ to $\frac{1}{16}$ in. on this same shaft

is required, a higher frequency of 200 to 500 kc. would be preferable. For the surface hardening of a pinion, say 5 in. o.d., ¾-in. face, 10 pitch, requiring a quick, shallow heat layer around the contour of the teeth, a high frequency would be preferable to one of 5,000 to 10,000 c.p.s., which most likely would penetrate a heat band through the entire tooth form.

Representative of the motor-generator-type set is the unit illustrated in Fig. 19, which has an output rating of 20 kw. The motor and the generator are located in the base, into which also are assembled the control board and the rectifiers. The upper section houses the output transformer, capacitors, and timer. At the front panel are located the two connectors for the heating coil, while at the front is located a suitable splash guard around the workpan. The unit shown has a single outlet station and is arranged for progressive hardening of the outer surfaces of steel shafts. The water quench is supplied through the heating coil, and is controlled by a timer which operates a solenoid valve.

These units are also made with two or three work stations and may be equipped with rotatable-type transformers so that the radial position of the heating coil can be adjusted as needed to accommodate certain types of workpieces. The transformers are of the iron-core type and have water-cooled primary and secondary.

When larger motor generators are required, they usually are located remote from the hardening or heating station. In Fig. 20 is shown an 800-hp. 500-kw. alternator used for the treatment of tractor gears, described in Chap. V. The motor and the generator both are totally enclosed and are hydrogen cooled. The generated current is 9,600 c.p.s. The unit includes four banks of capacitors to improve the power factor, and automatic-control equipment in three steps for regulation of the current during the heating cycle to compensate for the transformation taking place as the metal being heated passes its critical temperature and loses its magnetism.

Spark-gap Circuit. A typical circuit of a spark-gap converter is illustrated in Fig. 21. It resembles in many ways the spark-gap transmitters of early radio development. This circuit has been found effective for generating frequencies in the range from 100 to 200 kc. and is used more broadly in units having power-output ratings ranging from 2 to 15 kw.
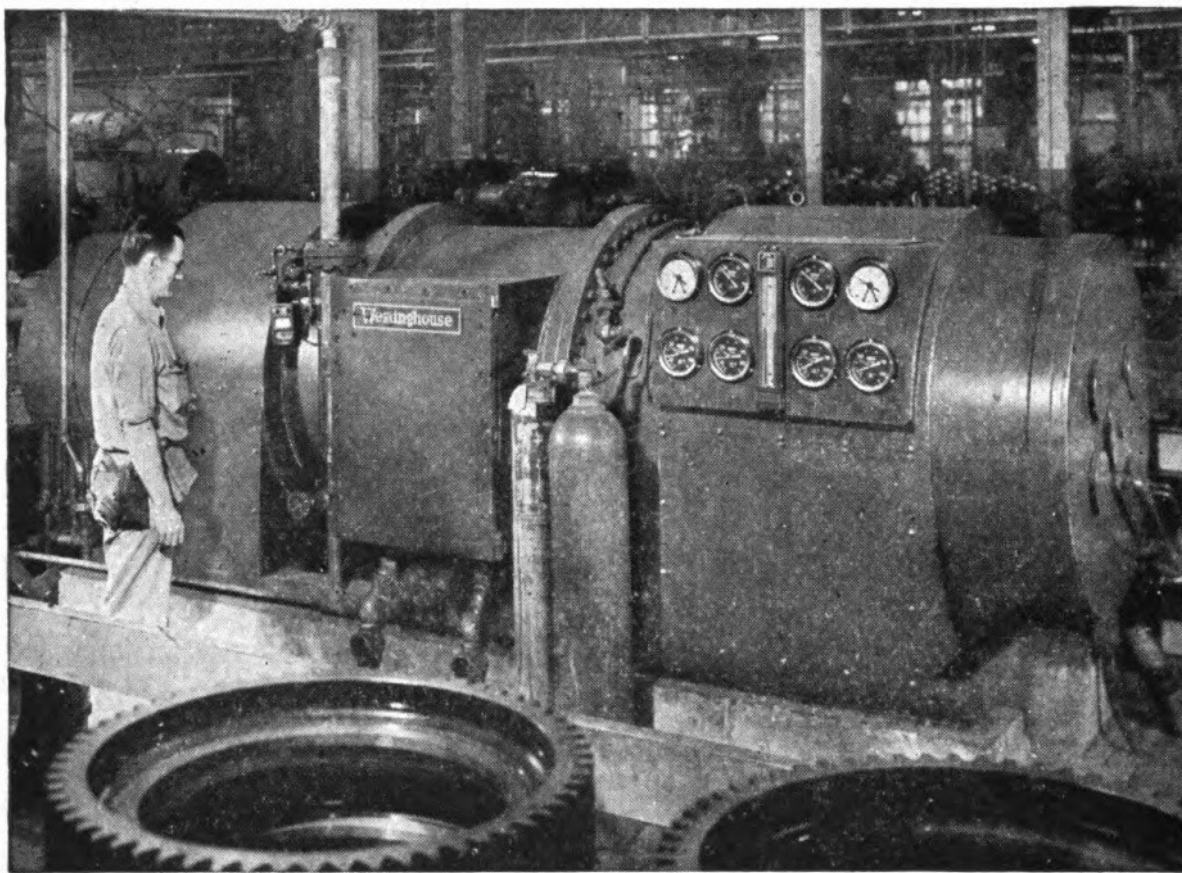
Fig. 20.—A large motor-generator set rated at 500 kw. with a frequency of 9,600 c.p.s. This unit is used for hardening a large tractor gear 26 in. in diameter with a 5-in. face. (*Courtesy of the Caterpillar Tractor Co.*)
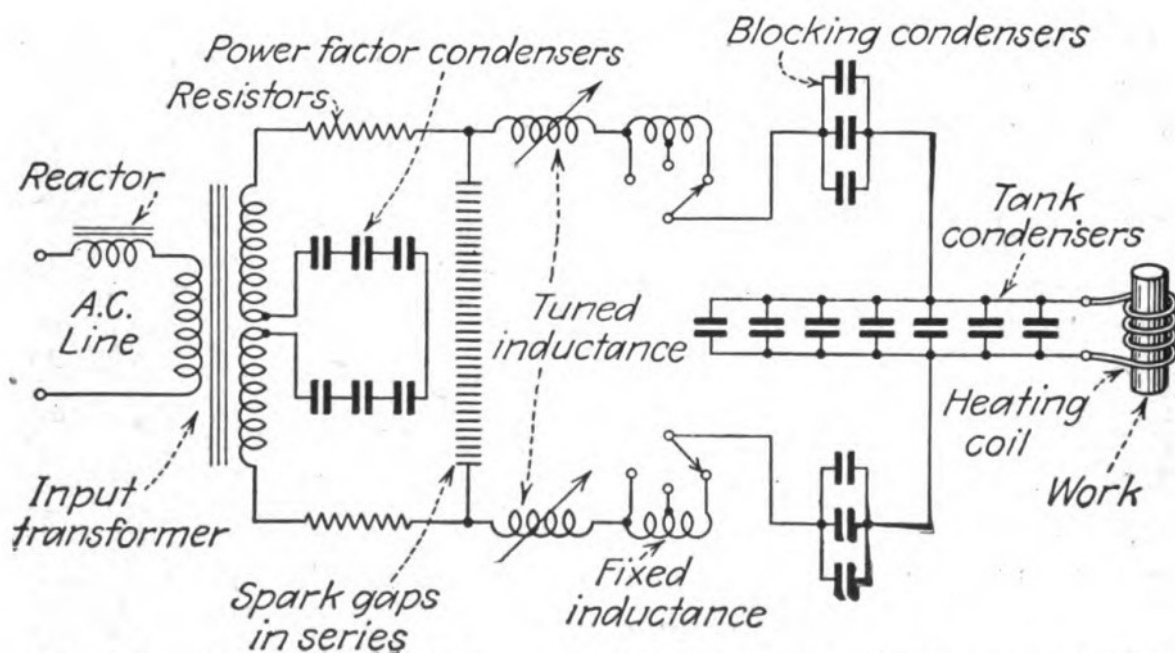

Fig. 21.—A typical circuit for a spark-gap converter having an output of approximately 15 kw. The heating coil is attached to leads that come direct from the tank circuit.

Water-cooled spark gaps with tungsten disks about 1 in. in diameter are used, with as many as 30 gaps connected in series in higher powered units so as to distribute the heat over a greater area. Ordinarily the gaps are checked with a feeler gage and readjusted to a spacing of 0.003 to 0.004 in. about every 25 to 50 working hours, to maintain peak efficiency and to keep the heating time uniform.

Each unit will usually have a few air-cooled gaps in series with the water-cooled gaps, to ensure starting of the spark, even though condensation on the water-cooled gap shorts them out for a time after the cooling water is turned on. A few minutes of operation will usually heat the gaps enough to drive off this external condensation of moisture. With extreme moisture present, however, the water used for cooling will require heating to a temperature that will overcome condensation.

The work coil and tank condensers form a parallel-resonant tank circuit which is, in turn, connected into a series-resonant circuit across the spark gap. Tuning involves adjusting the series tuning coils for maximum output current in the work coil as determined by a radio-frequency ammeter loosely coupled to the output circuit.

Maximum output current is obtained only when the series-resonant circuit is tuned to the same frequency as the output tank circuit. If a particular frequency is required, the series-tuning coils can be set for this frequency rather than for resonance if there is sufficient reserve power to permit operating the tank circuit off its resonant frequency.

Work coils used with spark-gap sets usually are limited to those made of flattened copper tubing, shaped to provide the necessary number of turns either around or inside the object to be heated. The majority of coils have from 2 to 10 turns. Cooling water is forced through the work coil and its connecting leads to prevent overheating during operation, since a coil may carry up to 1,000 amp. of radio-frequency current.

In spark-gap units, the radio-frequency output power can be switched on and off by a remote-control magnetic switch, operated by an automatic timer, foot switch, or small pilot switch. The work coil has only a few turns and the high-frequency circuits are balanced to give zero potential to ground at the center of the coil; hence the work coil can be touched by the operator while

power is on without harmful effects. Mica blocking capacitors prevent the high voltage across the spark gaps from reaching the work coil.

There is likely to be some radio-frequency radiation from the work coil and its leads. The radiation from the spark gaps
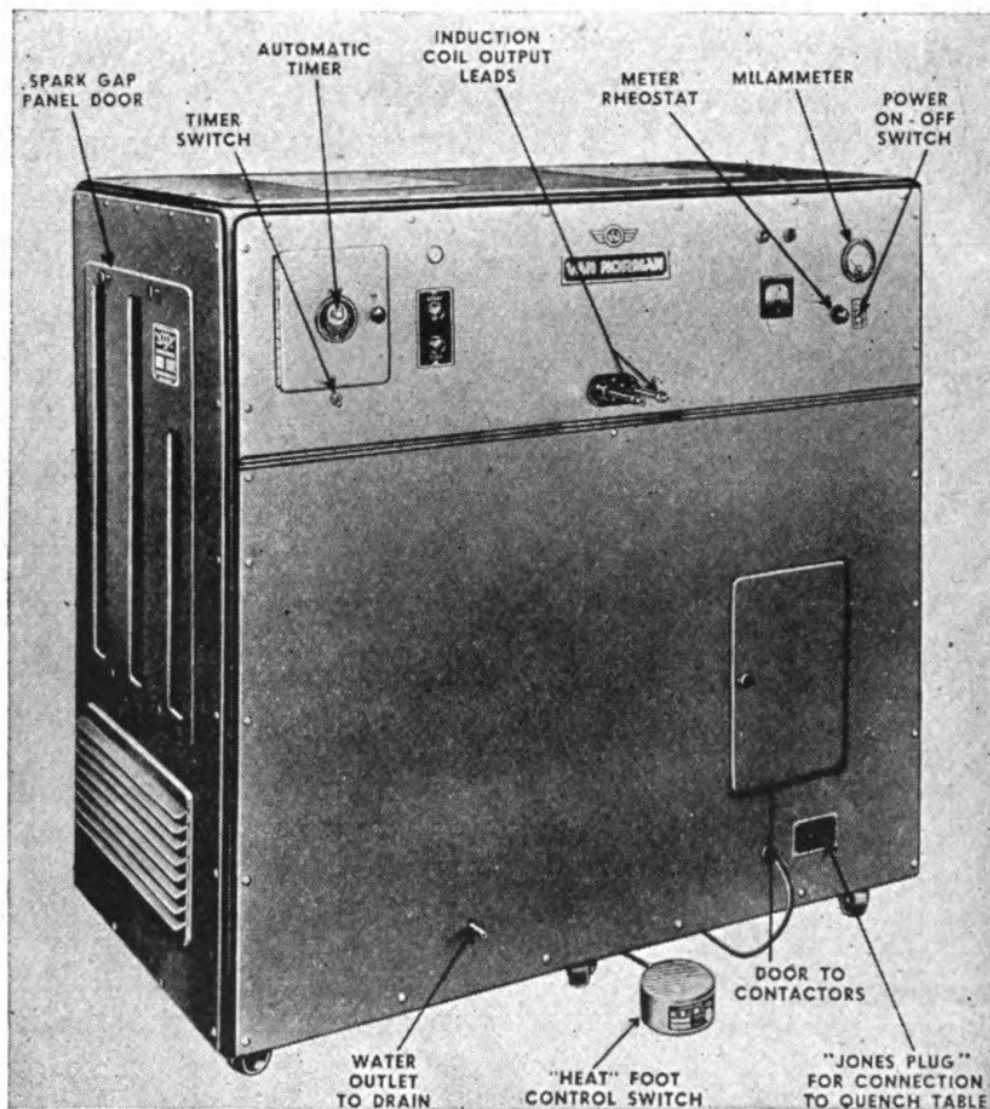

FIG. 22.—A representative type of spark-gap converter. All operating controls, as well as the output leads, are located on the front panel. (*Courtesy of Van Norman Co.*)

usually is spread over a wide portion of the frequency spectrum, but the energy at any particular frequency may travel only a short distance. In some instances where interference is observed, because of a peculiar combination of circumstances, the radiation can be eliminated by placing a metal screen completely around the unit.

In Fig. 22 is illustrated a spark-gap unit of 32 kw. input, showing the controls and outlet connections for the heating coil.

To this unit usually is attached a suitable worktable for brazing or hardening purposes. An interior view of the unit is shown in Fig. 23. Here may be seen the reactor and transformer in the lower center compartment, the large bank of spark gaps at the right, and the mica capacitors in the upper section. The entire assembly is mounted within a wooden frame so that stray high-frequency currents will not be absorbed or otherwise dissipated.
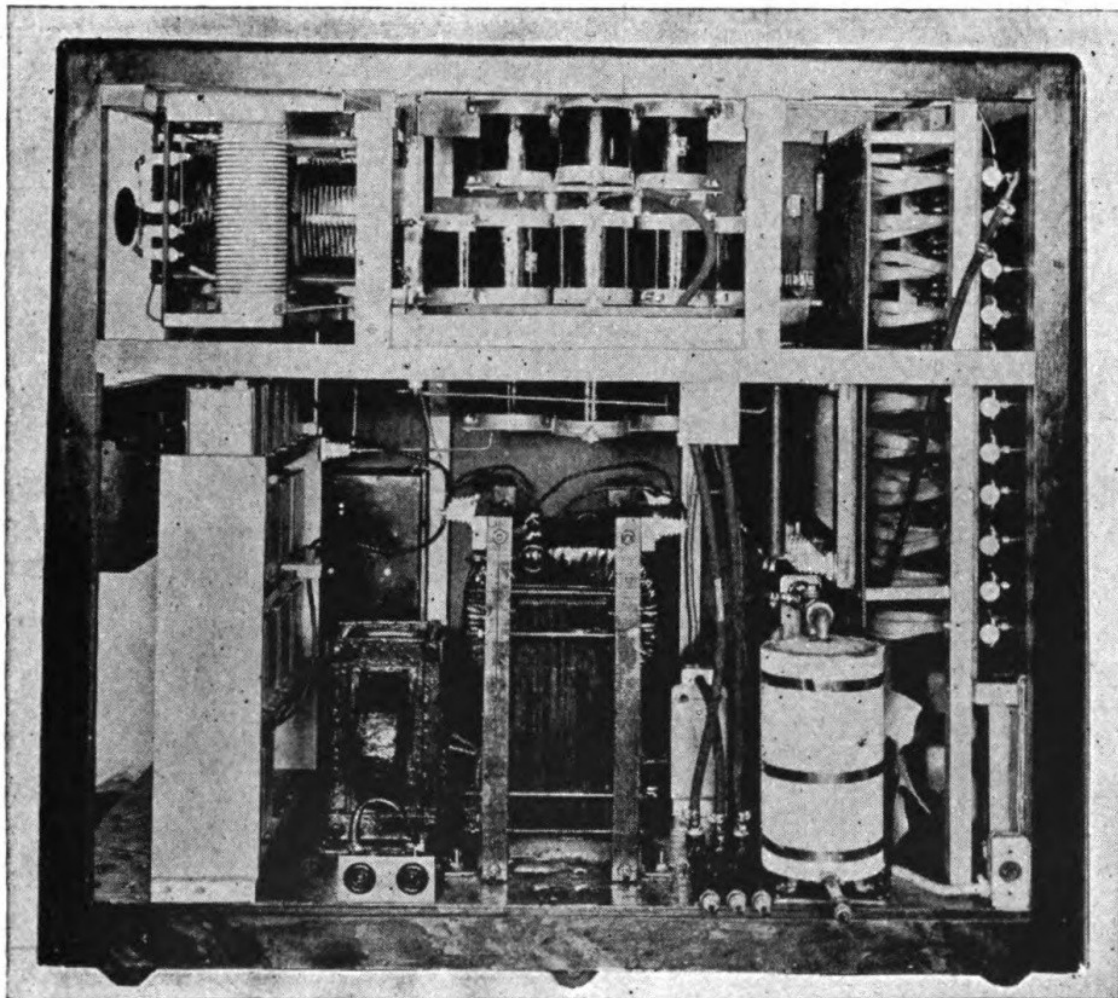

FIG. 23.—Interior view of a spark-gap converter having an input rating of 32 kw. The input transformer, power-factor condensers, tuned and fixed inductances; and tank condensers are shown. (*Courtesy of Van Norman Co.*)

A 20-kw. converter of the spark-gap type and a furnace capable of melting up to 17 lb. of metal are illustrated in Fig. 24, whereas a plan view of the installation may be seen in Fig. 25. The converter consists essentially of a high-reactance transformer, a discharge gap, and a bank of capacitors connected to the furnace coil. The frequency will vary generally between 25,000 and 40,000 c.p.s., depending upon the size of furnace used. Single-phase alternating current, usually 220 or 440 volts, is required.

The power efficiency will average about 50 per cent. The transformer is fitted with a high reactance and is contained in a non-magnetic oil-filled water-cooled case.

The capacitors are high-voltage, heavy-duty units, and each is self-contained in a sealed tank and adapted for individual water
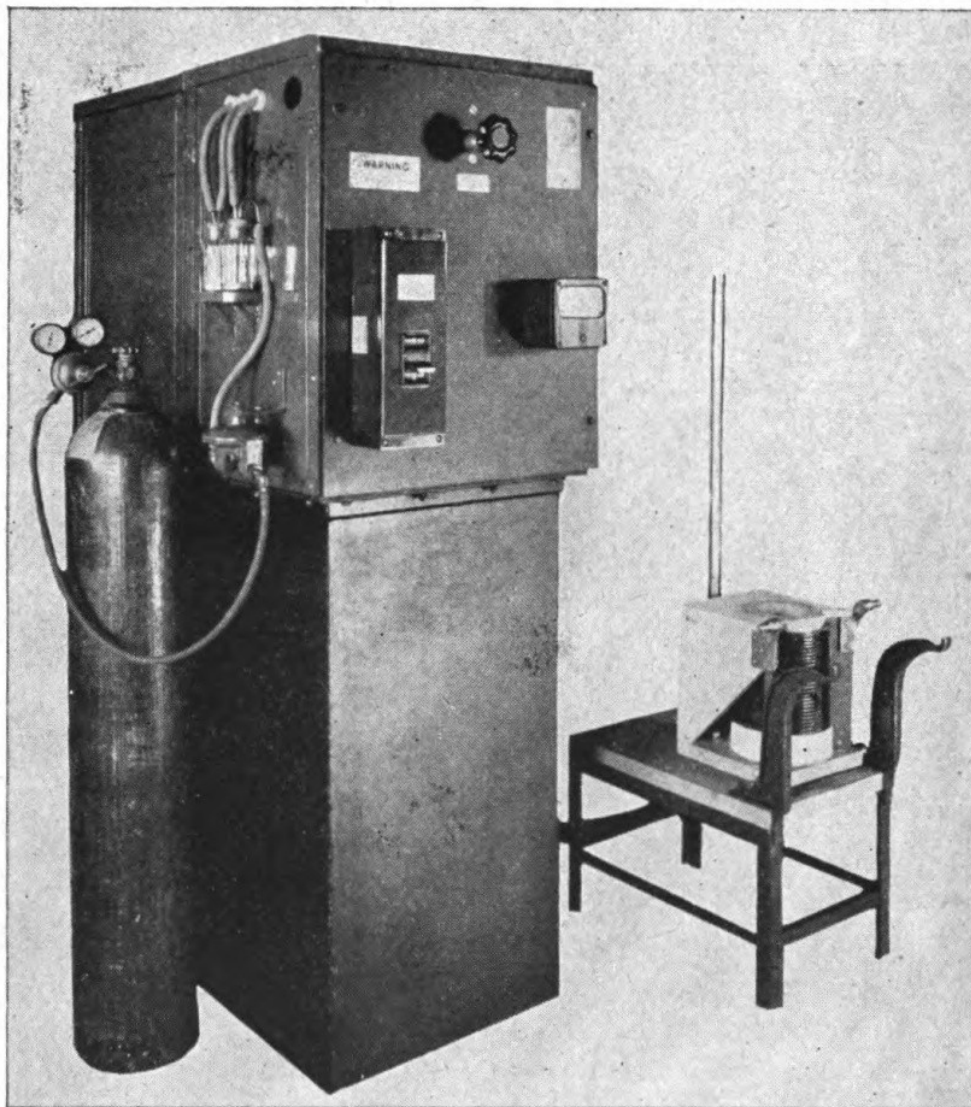

Fig. 24.—A 20-kw. converter of the spark-gap type is shown with a melting furnace at the right. This unit operates on a frequency of approximately 35,000 c.p.s. (*Courtesy of Ajax Electrothermic Corp.*)

cooling. The discharge gap comprises a mercury pool, two specially tipped copper electrodes, and an atmosphere of hydrogen, contained in a water-cooled chamber. The hydrogen is maintained in the gap by a pressure governor. Control of power is obtained by turning a handwheel that regulates the volume of mercury in the discharge-gap chamber.

The furnace comprises an electrical conductor, hollow and wound in a helix close to the charge to be heated. High-frequency current passed through the coil sets up an electromagnetic field about it, which induces current in a charge for heating or melting, or for stirring it after it is melted. As the electromagnetic field passes through the nonconductors without heating them, it is possible to heat or melt a charge without heating any of the surrounding material except as it may be heated indirectly by the charge itself.
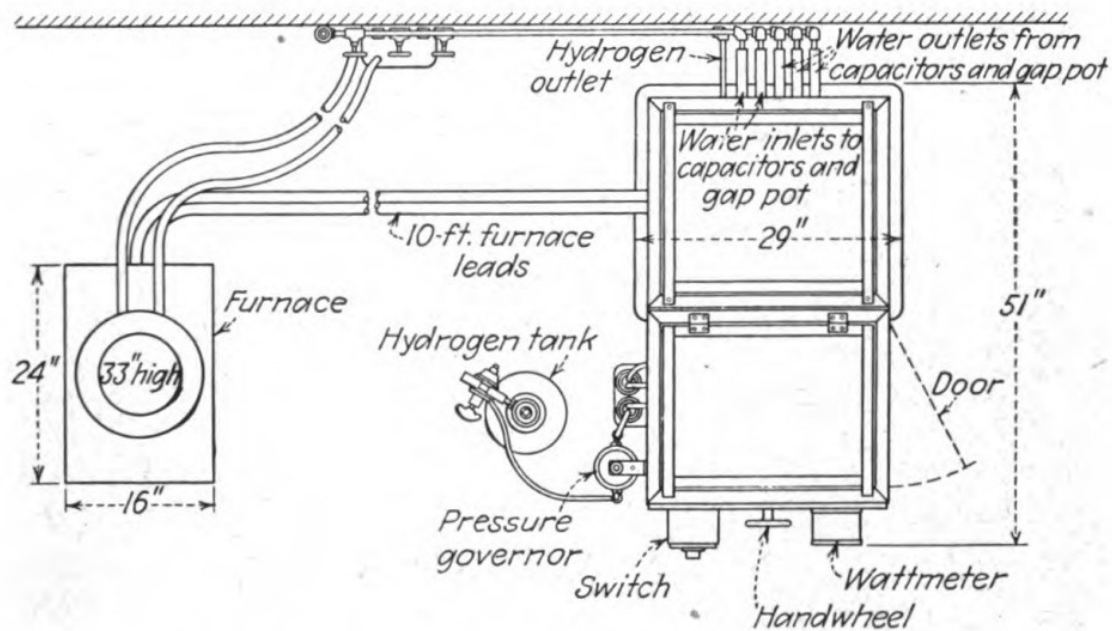

Fig. 25.—A plan view of a 20-kw. converter arranged for use in the melting of metals. The melting furnace shown at the left is remote from the converter and will handle capacities up to approximately 17 lb. of metal. (*Courtesy of Ajax Electrothermic Corp.*)

With this installation, a charge of 15 to 17 lb. of steel can be melted in a nonconducting crucible in about 50 min. A copper charge of the same size requires about 50 min. also, but when melted in a conducting-type crucible requires only about 18 min.

Tube-type Oscillator. A vacuum-tube-type generator with an output rating of 20 kw. is shown in Fig. 26. The two output leads are shown on the right-hand side. A view showing the interior of this set is illustrated in Fig. 27, while in Fig. 28 may be seen a simplified diagram of the electrical circuit. Only one manual control requires adjustment in connection with the operation of this generator.

The unit consists of two basic sections, the power-supply section and the oscillator section. The equipment converts ordinary

power-line frequencies to frequencies of the order of 375,000 c.p.s. The input energy is fed to a plate transformer in the power-supply section, which raises the voltage to approximately 10,000 volts. This 10,000-volt alternating current is then fed
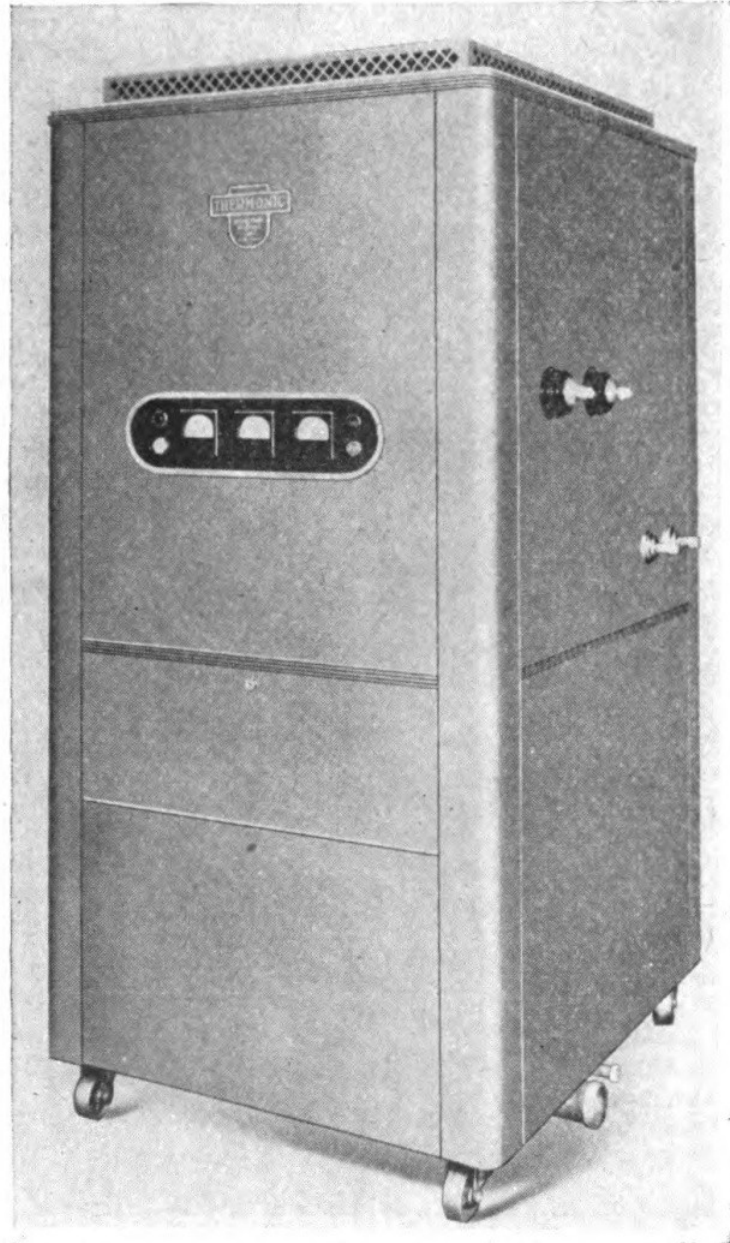

FIG. 26.—A typical generator of the vacuum-tube type is shown here. This set has a rating of 20 kw. output and operates at a frequency of 375 kc. (*Courtesy of Induction Heating Corp.*)

to a four-tube bridge-type rectifier that converts the alternating current to full-wave, rectified direct current at approximately 9,000 volts average value. The high-voltage direct current feeds the oscillator section through choke coils and by-pass condensers which prevent the feed-back of high-frequency energy into the power source.
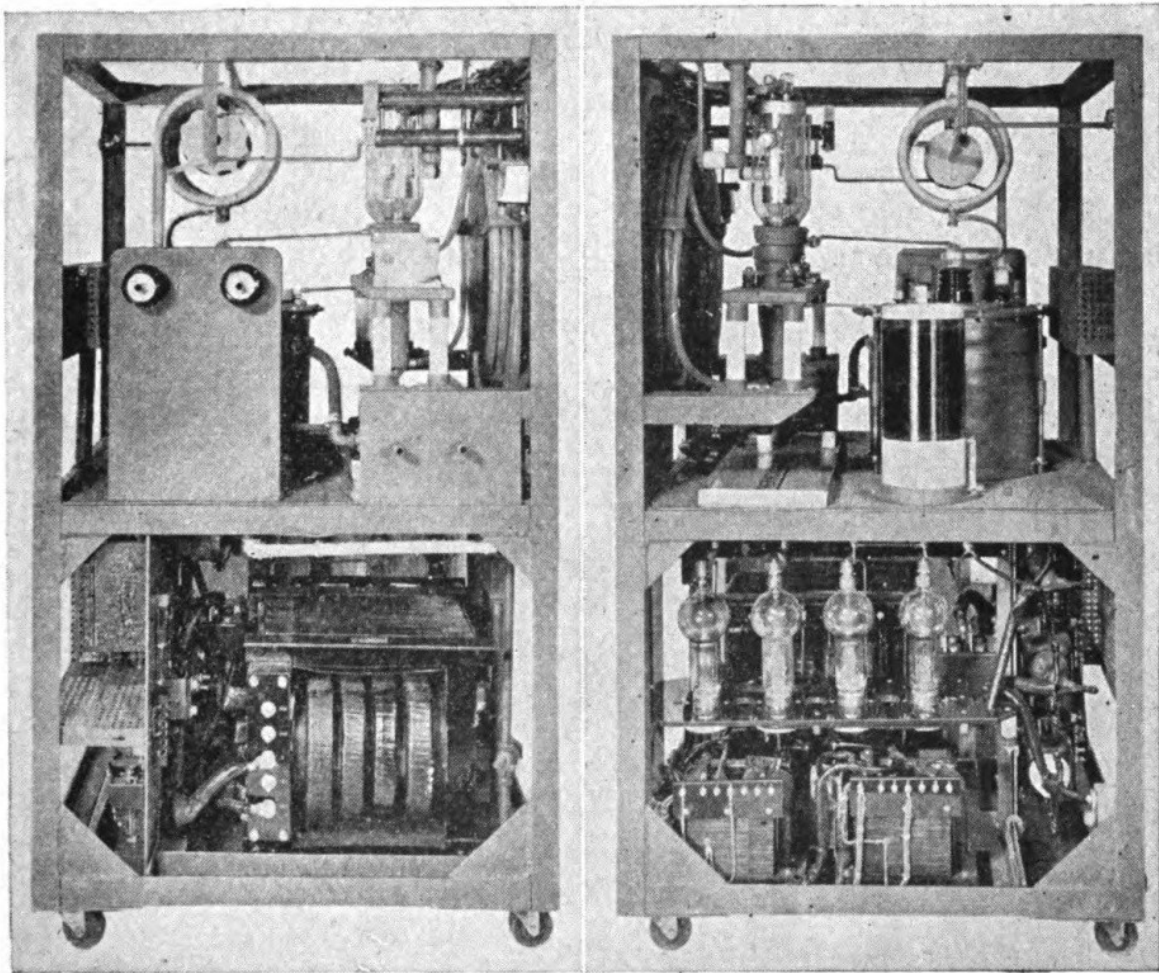
FIG. 27.—Interior view of a 20-kw. generator showing the power supply which is located in the lower compartment, and the oscillatory circuit which is positioned directly above.   (*Courtesy of Induction Heating Corp.*)
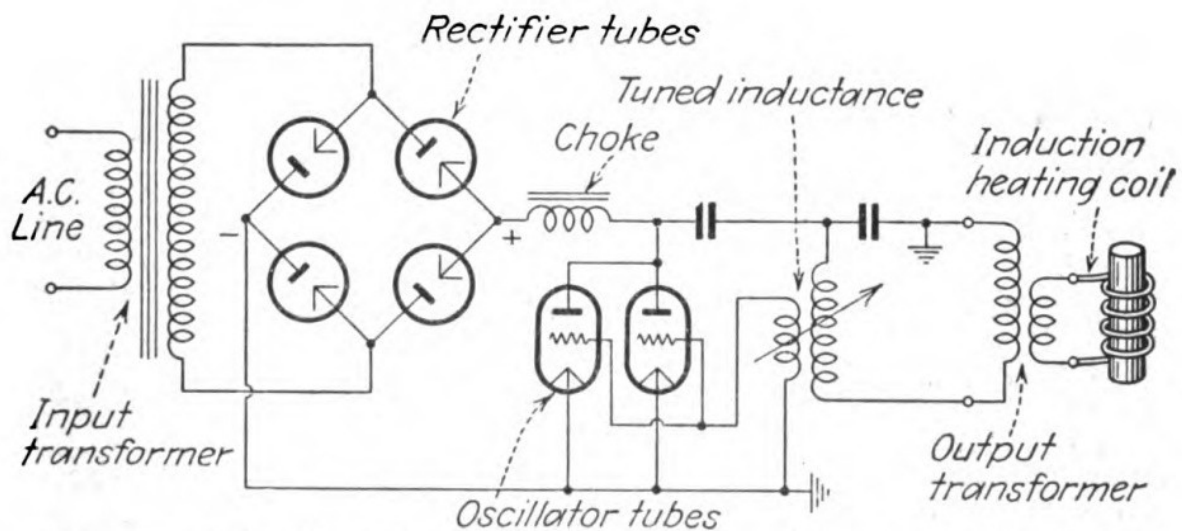

FIG. 28.—A simplified diagram of the generator shown in Fig. 26, having a rating of 20 kw. output.   The input line is stepped up to 10,000 volts, and then rectified, and finally fed through the oscillator section to the output leads. (*Courtesy of Induction Heating Corp.*)

The oscillator section consists of water-cooled three-electrode vacuum tubes, a tank circuit made up of a tank condenser and a tank-coil inductance, and a coil for feeding back high-frequency energy to the grids of the three-electrode vacuum tubes. The direct current from the power-supply section is applied across the plate and filament of the oscillator tubes, and the flow of current in these tubes is controlled by the action of the grid.
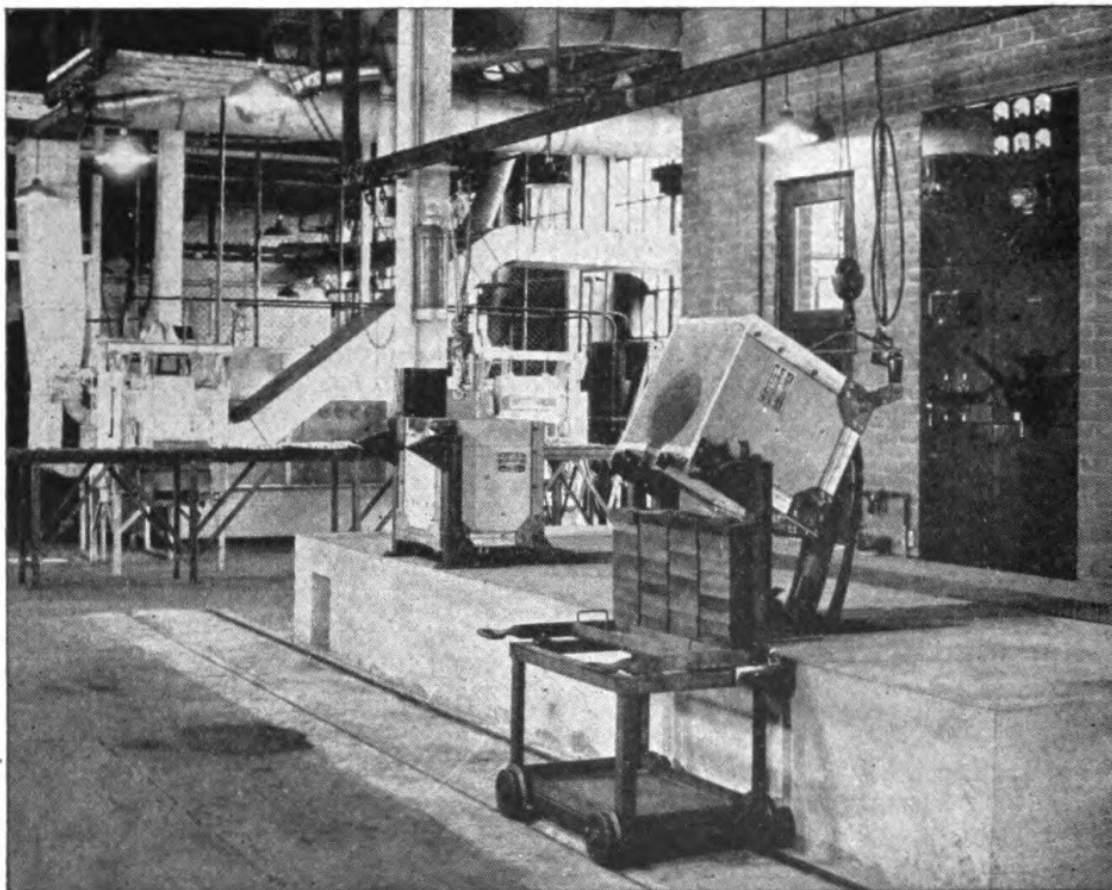

Fig. 29.—Induction-heating installation arranged for the melting of metals. This unit is rated at 60 kw. at 2,000 c.p.s., and handles up to 100 lb. of metal. (*Courtesy of Ajax Electrothermic Corp.*)

The oscillator tubes feed high-frequency energy through a blocking condenser, which prevents the passage of direct current but permits the passage of high-frequency current to the tank condenser and tank inductance. The tank circuit is designed so that it has a natural resonant frequency of approximately 375,000 c.p.s. When this circuit receives a direct-current impulse, its natural tendency is to oscillate at its basic frequency in exactly the same manner as a pendulum oscillates when it has received a mechanical impulse.

·When the tank circuit oscillates, alternating current flows in its component parts. This current produces a magnetic field that may be picked up by a coupling unit, and a small portion of the available energy is returned to the grids of the oscillator tubes. This grid energy causes the tube periodically to "block" and "fire" in synchronism with the resonant tank circuit. Thus,
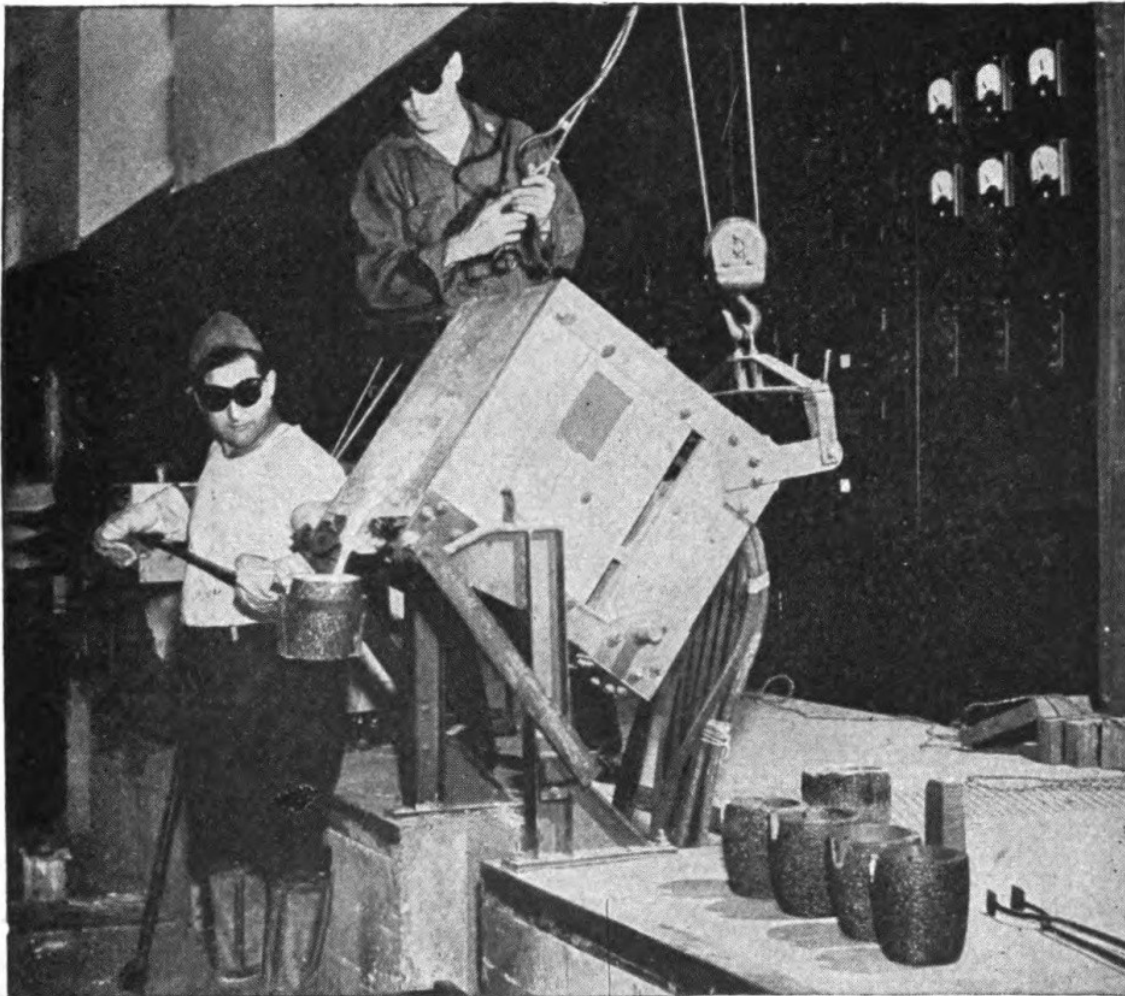

Fig. 30.—A close-up view of the melting furnace used with the induction-heating unit illustrated in Fig. 29. The furnace is equipped with flexible power leads, so that it can be tilted to facilitate pouring. (*Courtesy of Ajax Electrothermic Corp.*)

impulses of energy are fed to the tank circuit at exactly the right moment so that the oscillations are continuous and do not decay with time as the motion of a pendulum decays after having received only one mechanical impulse.

The circulation of this high-frequency current in the tank current makes available energy for use in various applications. In induction heating it usually is desirable to circulate a large high-frequency current in a water-cooled "work coil," which

surrounds the work being heated. If a step-down transformer is interposed between the inductance of the tank circuit and the work coil, it is possible to increase the current available in the work coil and at the same time reduce the voltage applied to it. In order to obtain optimum heating results with this type of
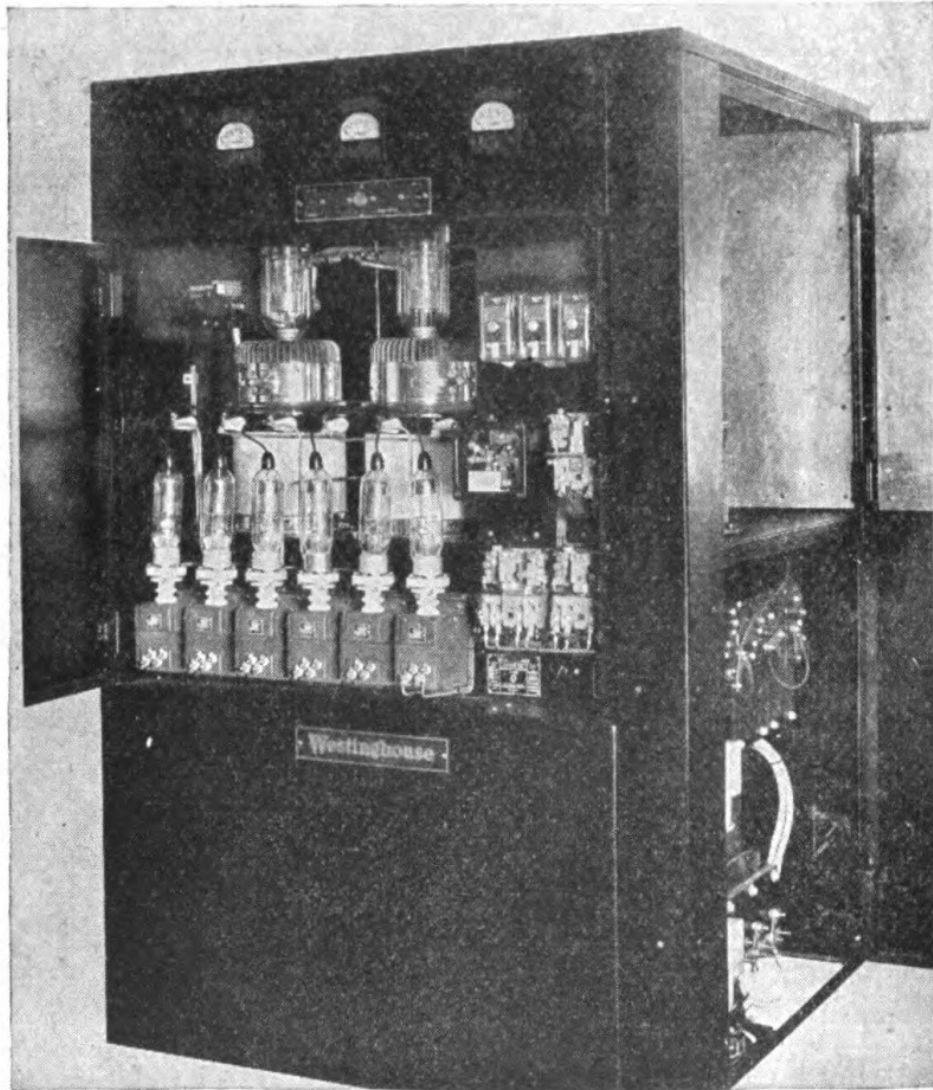

FIG. 31.—A high-frequency induction-heating unit of the electronic type, rated at 20 kw. output and operating at a frequency of 200 kc. A bridge-type rectifier using six tubes is included in the power-supply circuit. (*Courtesy of Westinghouse Elec. & Mfg. Co.*)

equipment, it is necessary to have the electrical impedance of the work coil match the terminal impedance of the generator. This is accomplished by having several types of transformers so designed that they cover the usual impedance range of the various work coils encountered in industrial applications. These transformers permit the circulation of very heavy currents at very low voltages, which in turn make it possible to heat many

objects with a simple, single turn of copper tubing or a single-turn copper block.

The filaments of the rectifier and oscillator tubes are energized from small-filament transformers. Power is applied to the work by energizing the plate circuit of the oscillator by a push-button control, located adjacent to the working position. A timer which may be set at will to any desired value is incorporated in
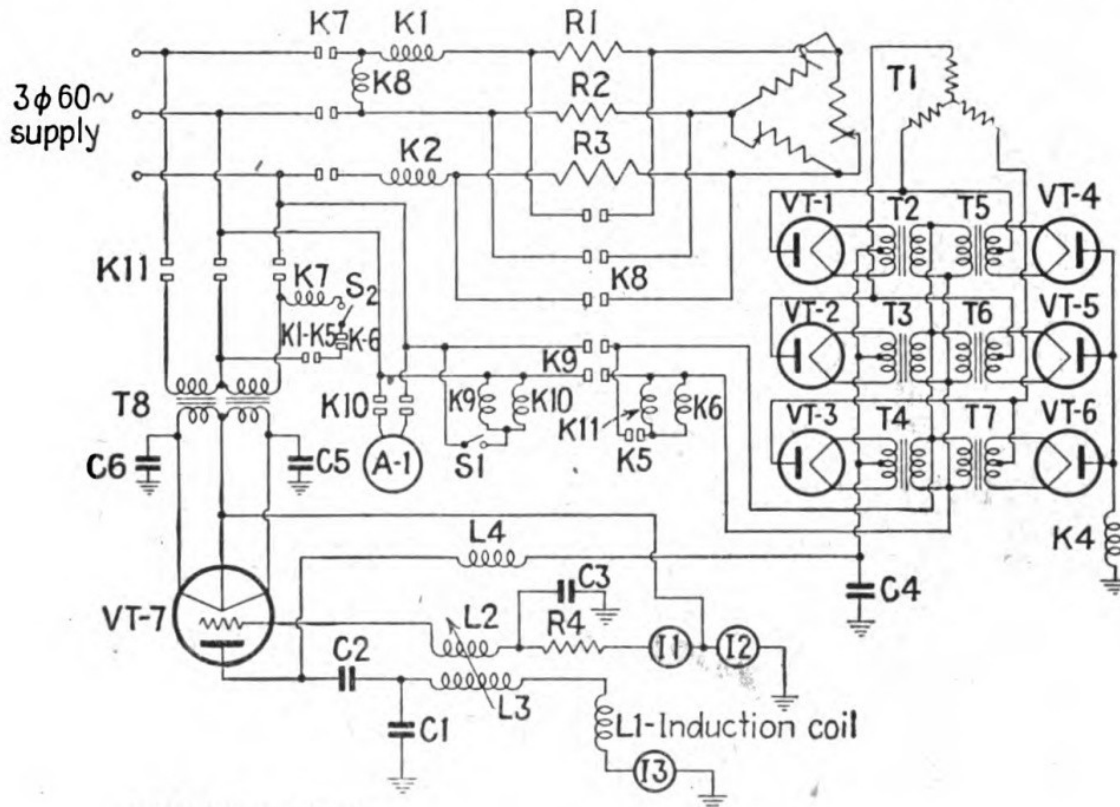
SYMBOL LEGEND:
C-Capacitors   L-Coils   T-Transformers
K-Relays-Starters R-Resistors   VT-Tubes

FIG. 32.—Another typical electronic-type circuit is illustrated here. The circuit is provided with a number of safety devices. (*Courtesy of Westinghouse Elec. & Mfg. Co.*)

the generator. This timer automatically shuts down the equipment as soon as the predetermined heating cycle has been completed. Pushing the button restarts the timer and the operation is automatically repeated.

Several protective devices are incorporated in the equipment. In the event of water failure to the oscillator tubes, one of two devices will function. These are a flow switch which operates on gallons per minute flow only, and a pressure switch which operates on pounds per square inch only. A reduction in

flow of water or pressure will automatically trip these devices. An overload relay is installed in the plate circuit so that, if excessive power is drawn from the equipment, it will be tripped automatically from the line. A time-delay relay is installed in the equipment to prevent application of plate voltage before the filaments of the tubes are sufficiently heated on starting of the equipment.

Miscellaneous Equipment. A somewhat larger type of induction-melting installation is shown in Fig. 29. In this unit,
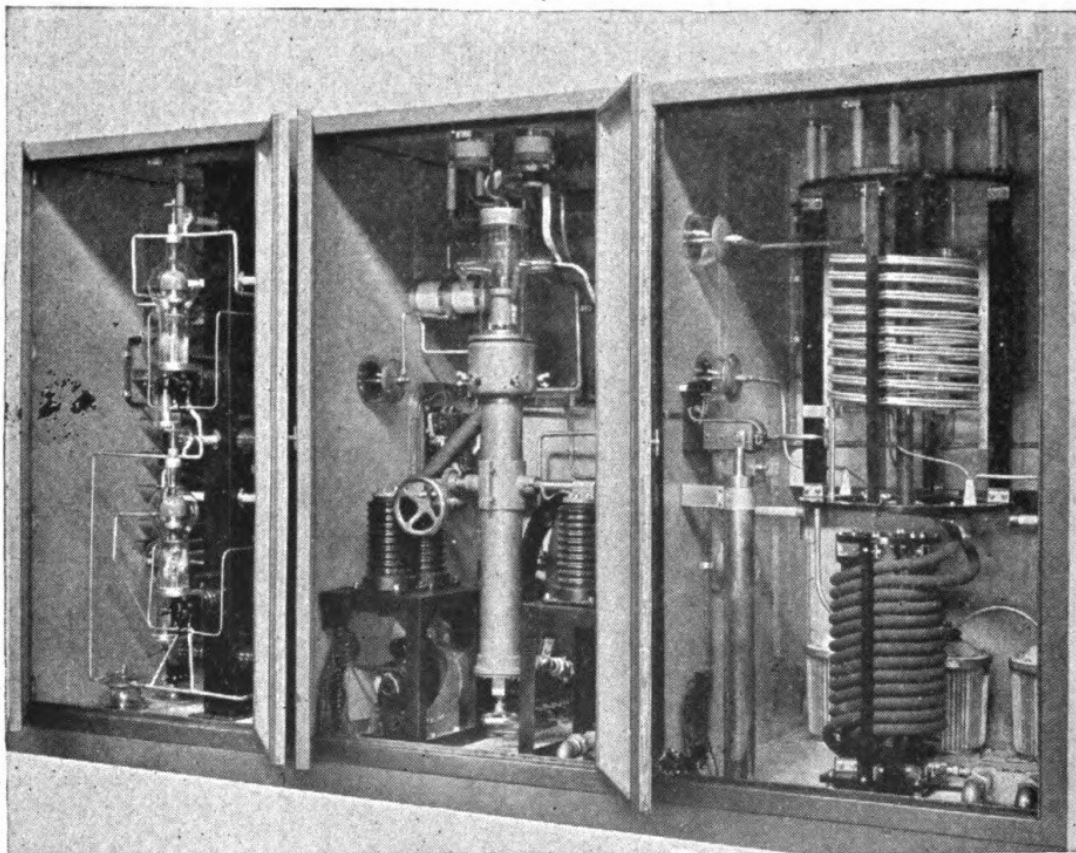

FIG. 33.—This illustration shows a large three-section high-frequency generator arranged to provide a 100-kw. output at a frequency of 200,000 c.p.s. (*Courtesy of Westinghouse Elec. & Mfg. Co.*)

power is obtained by means of a motor-generator set located directly behind the control panel seen at the right. On the panel are mounted the circuit-breaker ammeter, voltmeter, power-factor meter, wattmeter, and rheostat handles for voltage control. This installation is used for melting steel alloys and operates at 2,000 c.p.s. 60 kw. power. The furnace handles 100 lb. of metal, which can be melted in approximately 30 min.

A close-up view of the furnace, pouring a charge of alloy steel, is illustrated in Fig. 30. The furnace is built as a tilting unit

and is provided with flexible cable leads, which enable power to remain on during pouring. This is advantageous when several castings are poured from one heat, since the molten metal remains at correct pouring temperature regardless of the time interval between castings.
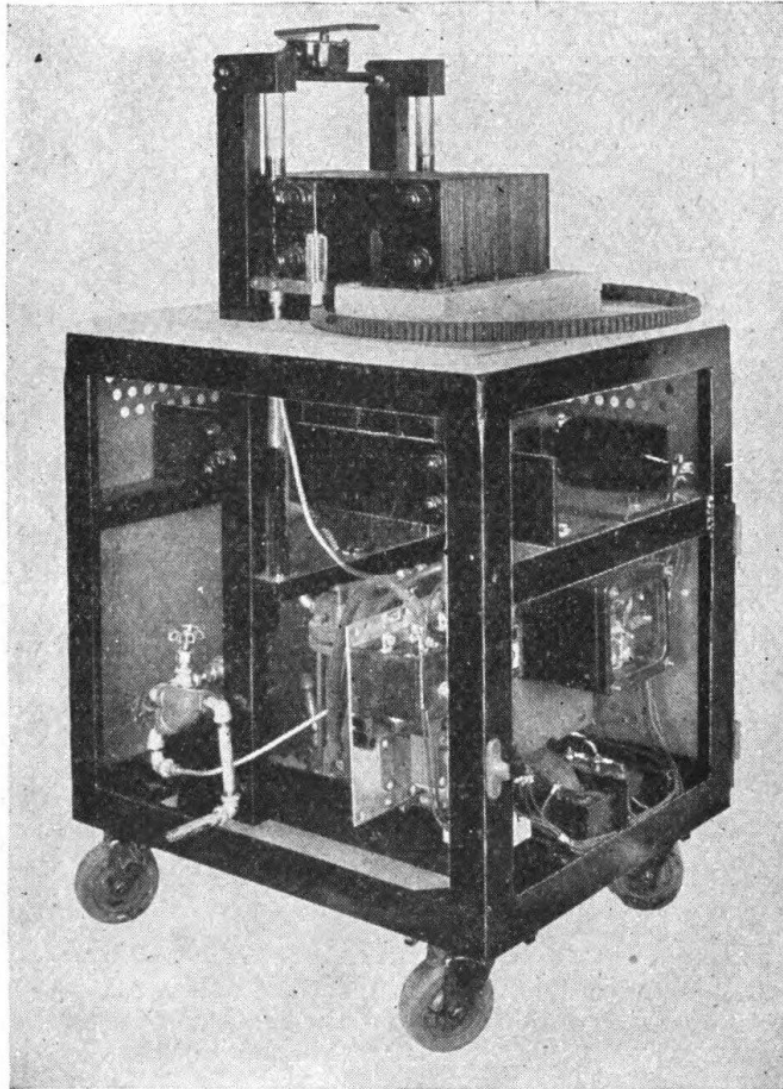

FIG. 34.—An induction heater of the lower frequency type, which is used for the heating of steel parts where relatively low temperatures are desired. (*Courtesy of Ecco High Frequency Corp.*)

Another type of vacuum-tube induction-heating generator is illustrated in Fig. 31. It has six rectifier tubes and two oscillator tubes, and is rated at 20 kw. output. A circuit diagram of a similar generator employing one oscillator tube is illustrated in Fig. 32.

In Fig. 33 is shown a three-section generator capable of delivering 100 kw. at a frequency of 200 kc. The section at the left

contains the rectifier portion of the circuit, and the center and right-hand sections the power-oscillator tube and oscillator circuit. This unit furnishes the high-frequency power for the flowing of tin plate, described in Chap. VII.

Low-frequency Heater. Another type of induction-heating unit which is used for the expansion of steel parts that are to be
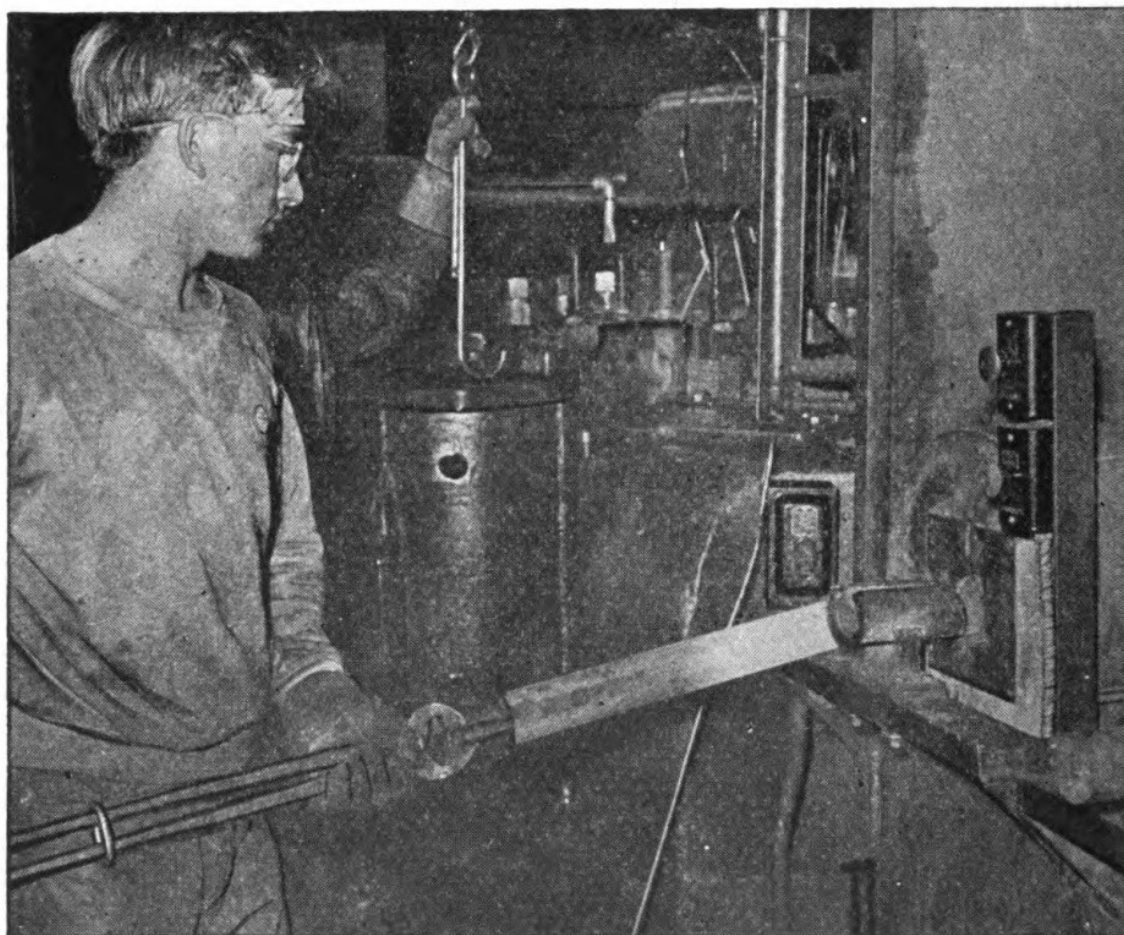

FIG. 35.—A heating unit used in connection with a motor-generator set is illustrated here. The operation comprises the heating of the end of steel bars for forging purposes. (*Courtesy of Ajax Electrothermic Corp.*)

shrunk onto shafts, such as gears onto fly wheels, is illustrated in Fig. 34. This heater operates on a relatively low cycle of 50 or 60 c.p.s. and usually is applied to the heating of parts up to 500 or 600°F. This unit is shown with the sides removed and, as will be seen, comprises an iron-core transformer which is opened and closed by means of a pneumatic cylinder to facilitate insertion and removal of the gear or part to be heated. The transformer in this case is the primary of the circuit, whereas the gear itself forms a one-turn secondary winding.

The unit shown has a rating of 15 kva. and accommodates rings from 12 to 36 in. in diameter. The heater is provided with automatic timer so that the cycle can be duplicated once the proper heating time has been established.
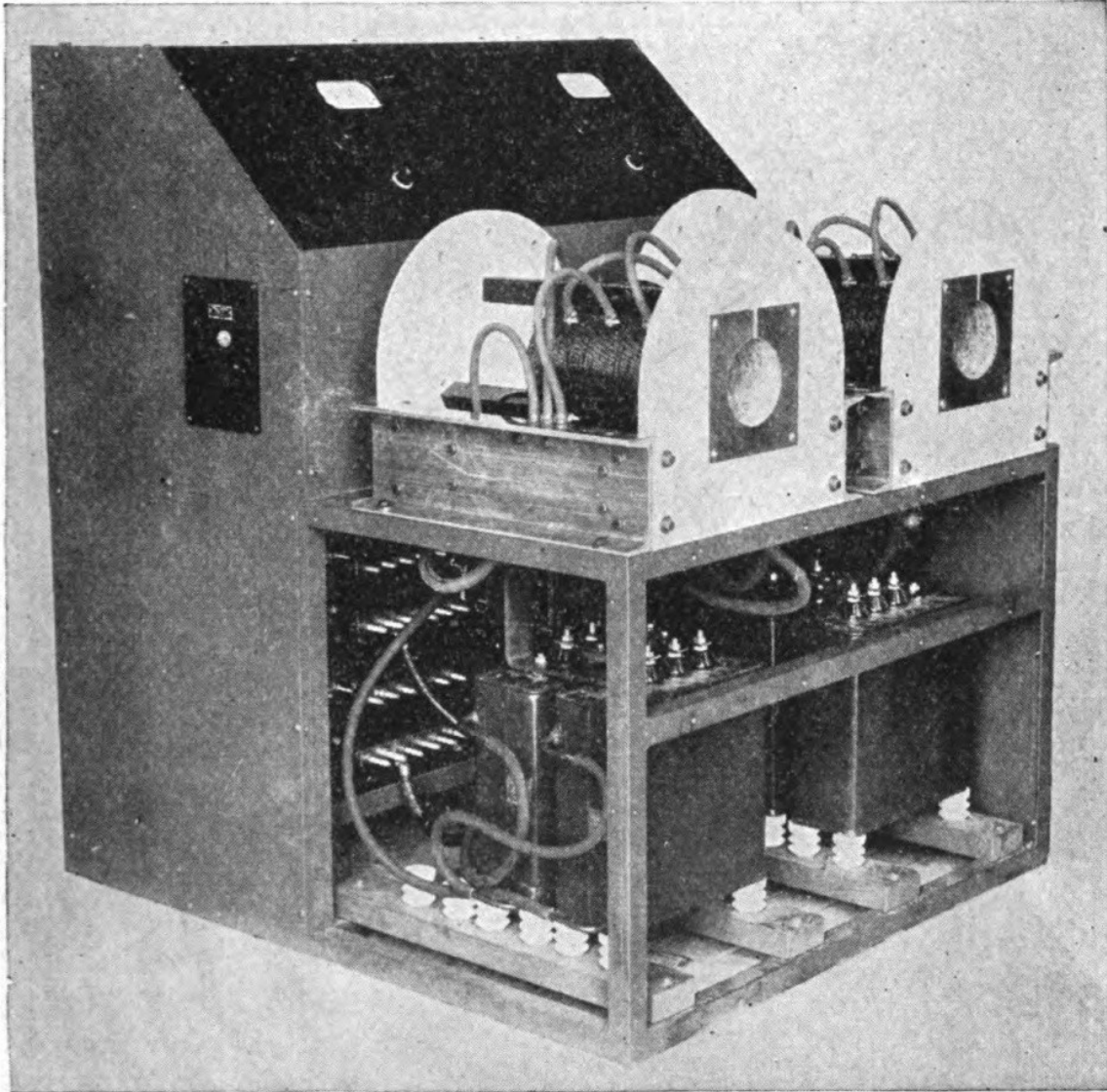

FIG. 36.—Interior view of a two-station heating unit used for the heating of bars which require forging. Power supplied by an 80-kw. motor generator operating at a frequency of 2,000 c.p.s. (*Courtesy of Ajax Electrothermic Corp.*)

In Fig. 35 is shown at the right a single-station heating unit of the motor-generator type, as used for forging. The steel bar being heated is 28 in. in diameter, and is heated to 2200°F. at one end, as may be seen. The heating unit is located adjacent to an upsetting press, so that the heated bar can be transferred quickly from one to the other.

A similar heater equipped with two heating crucibles is shown in Fig. 36. The side plates and covers have been removed to

show the internal construction. These furnaces are loaded manually but otherwise are controlled automatically with regard to the time and heating cycles. An end of a 2-in. bar can be heated to 2200°F. in approximately 2 min., and the power required for heating is from 0.2 to 0.25 kwhr, per pound of metal heated. This unit is powered by an 80-kw. 2,000-cycle motor generator.

CHAPTER III

DESIGN OF INDUCTION-HEATING COILS

Coils for high-frequency induction heating can be made in a wide variety of styles, shapes, and sizes. Their design usually is governed by the nature of the component to be heated and by the type of generator used. Briefly, coils can be of the single-turn or multiturn type, fabricated, multiple, series-connected, or cast to shape. However, some high-frequency generators are limited to certain specific types of coils, because of the impedance of their tank circuits which may limit their use to multiturn coils. In view of this condition, the power source must be taken into account before a heating coil is designed. Other generators, however, are provided with means to match practically any type of heating coil so that a much broader selection of coil designs is made possible.

In describing different types of heating coils for inductive operations, it would be difficult to cover all the different types of conditions which arise, such as the shape and size of the work piece, the nature of the surface to be heated, and its relation to the heating coil. However, from the variety of heating coils shown, representing the designs most commonly used, together with some of the basic principles involved, a good conception of the importance of coil construction will be gained. The designs represent coils that will serve the need for a wide variety of heating operations, and that with slight modifications will cover the majority of heating applications encountered.

Perhaps nothing is more important to induction heating than the coil itself. Next is the source of power, which must be suited to the particular operation contemplated. It is here that frequency and volume of power show their possibilities as well as their limitations. But with suitable high-frequency power it is on the coil that we depend for the correct distribution of heat within a metal part.

If we consider a heating coil as a means of transferring heat by eddy currents, and then consider the shape of the coil in

relation to the work's surface, we can see that the heat pattern will closely resemble the shape of the coil, more so with a close coupling than where the work and the coil are farther apart. The problem therefore is to make the coil of correct shape to surround a surface to be treated and then space it according to the amount of heat needed. As the coil is placed farther from the work, the eddy currents spread out in wider form and cover a larger surface. Coupling, therefore, is an important consideration.

Not always is maximum heat transfer the most desirable factor. Often a slow, even heat distribution is the outstanding
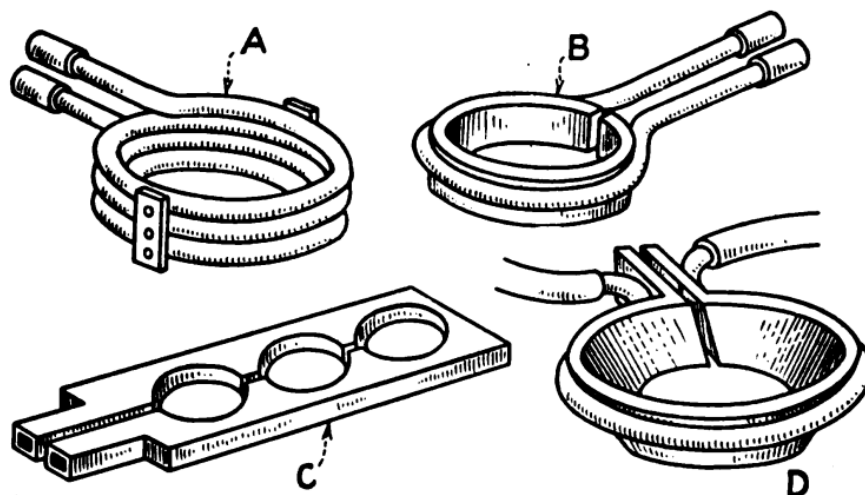

FIG. 37.—A variety of heating coils used in connection with induction heating operations, including those of the single- and multiturn types.

need. For general hardening purposes a quickly and rapidly heated surface usually is desired. For soldering a slower penetrating heat might be more desirable. For brazing a somewhat in-between heat might be required, since rapid heat might cause blistering and a slow heat would result in lost time or the heating of unwanted areas.

Types of Coils. In Fig. 37 are illustrated some of the more commonly used coils as applied to induction-heating operations. The general-purpose type most used is the one shown at *A*, representing the multiturn design, which is wound or formed from copper tubing, either symmetrical in contour or shaped to suit the outline of the part to be heated. Solid-type inductor coils, like the one shown at *B*, are also widely used and are particularly suitable for the heating of parts where a restricted

heat zone is desired. The coil shown at C is of series design, which makes possible the heating of several pieces at one time. The coil at D is made of flat strip, which, as may be seen, may be used in a variety of heating operations.

Regardless of the type of coil used, it is necessary to provide cooling, which in the case of the multiturn coil is accomplished by circulating a flow of water through the coil itself. With the single-turn inductors, cooling is accomplished by adding a copper tube to the outside or by other suitable cavities for the passage of water.

Round A   Rectangular B   Formed C

Pancake D   Spiral-helical E   Internal F
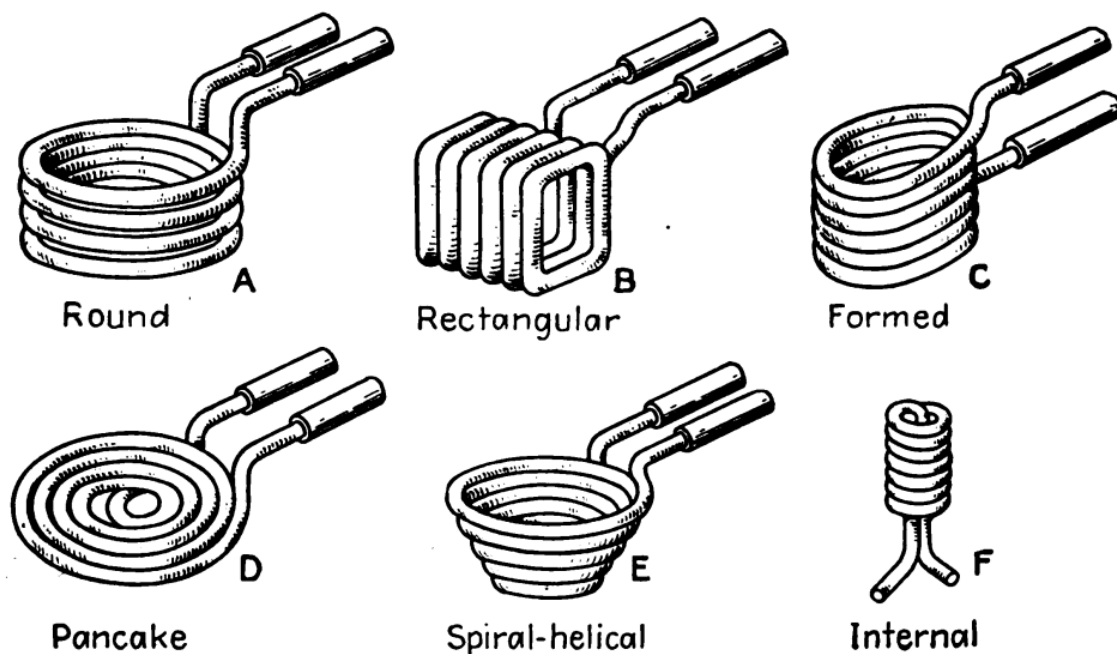
FIG. 38.—Multiturn coils can be formed to various shapes and usually have a wide latitude of applications in connection with induction heating work.

All heating coils, regardless of their design or shape, should be made of copper having a conductivity of 90 per cent or more. Pure copper unquestionably serves as the best material for coil construction.

Multiturn Coils. In making multiturn coils of copper tubing, a wide variety of shapes is possible, as shown in Fig. 38. The most common is a cylindrical coil, as at A, which is suited to surface-heating of shafts and round parts. The rectangular or square coil at B, as well as the cam-formed coil at C, also is used for heating the outer surfaces of bars or shafts and can be easily formed and wound over a wooden block. The pancake coil at D is used for heating flat surfaces, such as clutch jaws, or ends of shafts, while the spiral-helical coil E is used for heating conical

surfaces, such as bevel gears. The coil at *F* is of the internal type and is used for heating inner surfaces of holes.

Other suggested types of induction coils made of copper tubing, arranged for heating irregular surfaces, may be seen in Fig. 39. The coil at *A* heats the surface around the slot, while the one at *B* heats the end section of a formed steel bar. Coil *C*, somewhat similar in shape, heats one edge and the fillet of a plate, cne view of which illustrates the coil in position during heating. With irregular surfaces such as these, requiring coils of intricate shape,
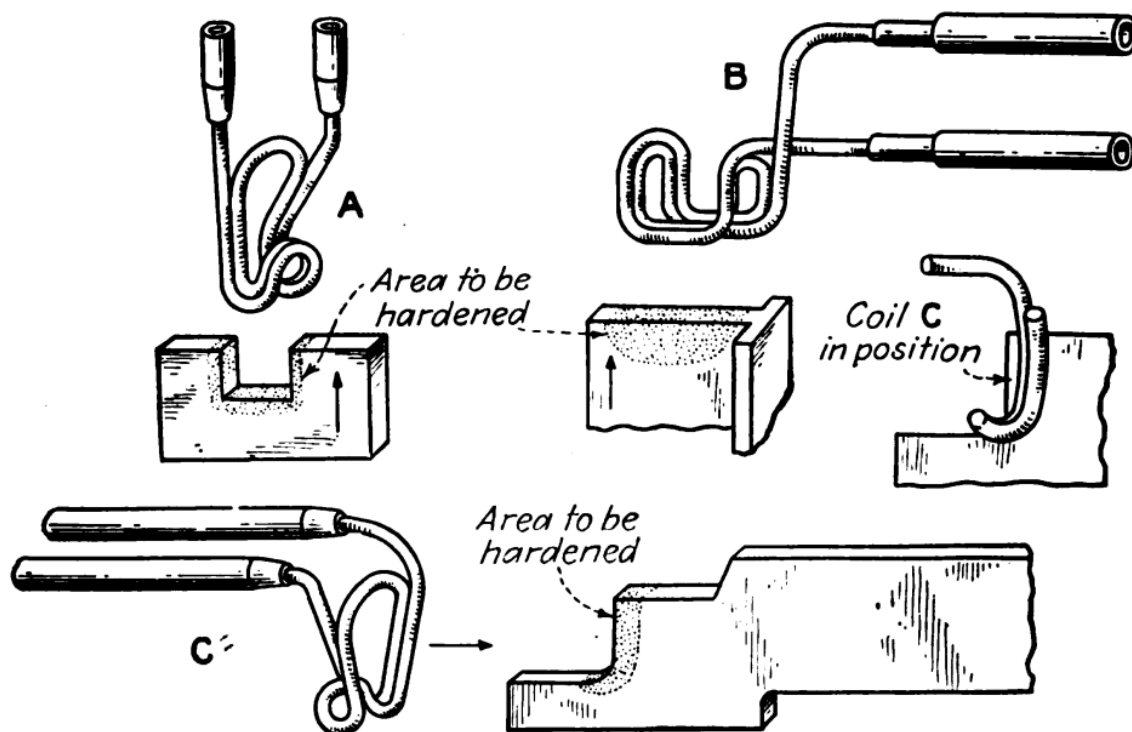
Fig. 39.—Copper tubing can be formed into various odd-shaped coils, as shown, for the localized heating of metal parts.

it is often necessary to experiment until the correct heat pattern is obtained. Sometimes only the spreading of the coil, one way or another, might offer the results desired, whereas in other cases a completely new shape may have to be wound.

In Fig. 40 suggestions are shown for the construction of copper-tube coils. Such coils usually are made of tubing ranging from ⅛ to ¼ in. in diameter. The ⅛-in. size should be used very sparingly, however, because of its small area and since the flow of cooling water is likely to be too small to prevent overheating. For short heating cycles, where a slight heating of the coil may have no effect, this size could be considered. However, the two larger sizes are preferable.

Round copper tubing can be used for many types of coils, as shown in *A*, although it is usually preferable to flatten the tubing as illustrated at *B*. Another practical form is the square or rectangular shape shown at *C*. It also is possible to use a larger diameter tubing, such as ⅝ or ¾ in., as shown at *D*, and to produce a flat coil similar to a solid inductor previously mentioned.

In making helical copper-tube coils where a restricted heat zone is desired, the coils should be made with an offset, as shown at *E*, so that uniform heating can be provided. At *F* is shown

Round   Flat   Square   Flat

A   B   C   D

Copper Tubing

Offset in Coil for
Uniform Heating

Brace for Large Coils
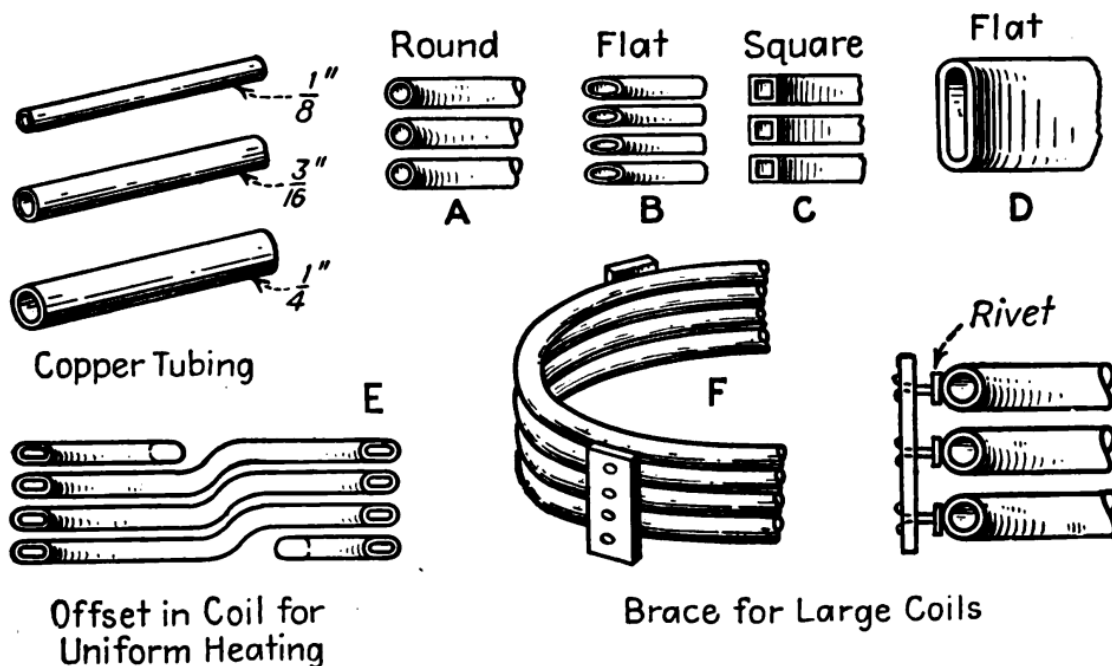
Fig. 40.—Constructional details of copper-tube heating coils of the multiturn type are shown here.

a means of providing a brace for large-diameter coils, which might have a tendency to sag or go out of shape. These braces provide unusual stiffness and, as shown, are attached by brazing small rivets to the coil section and heading the rivets over on the outside of the braces. These braces can be made of thin asbestos board, or a laminated plastic material.

A suggested form of tube flattener for use in the making of heating coils requiring square, oval, or other formed sections, is illustrated in Fig. 41. This device consists of two formed rolls, through which the copper tubing is passed. Feeding of the tubing through the rolls is done by means of the hand crank. The upper roll is mounted on a hinged bracket, which is adjusted

to correct relation with the lower roll by means of the hand knob *B*. At *C* is shown the type of roll which can be used for forming a square-shaped section from a round tube, whereas at
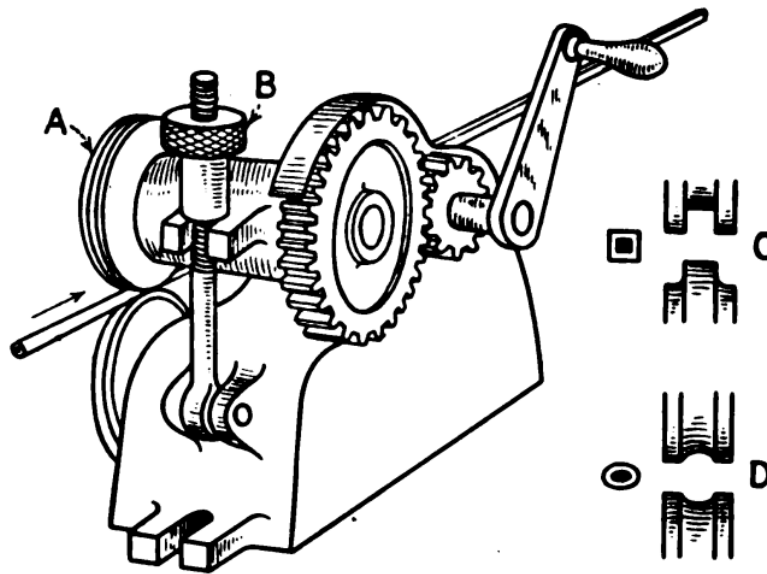

FIG. 41.—A hand-operated tube flattener, provided with forming rolls, can be used in the construction of heating coils requiring flat tubing.

D is illustrated the roll used for providing an oval- or flat-shaped tubing.

Heating Rates. Because of the path of magnetic flux around a cylindrical coil like that at *A*, Fig. 42, the greatest field strength will be obtained within the coil itself, rather than on the outside.

External Coil   Flat or Pancake   Internal Coil
                     Type Coil
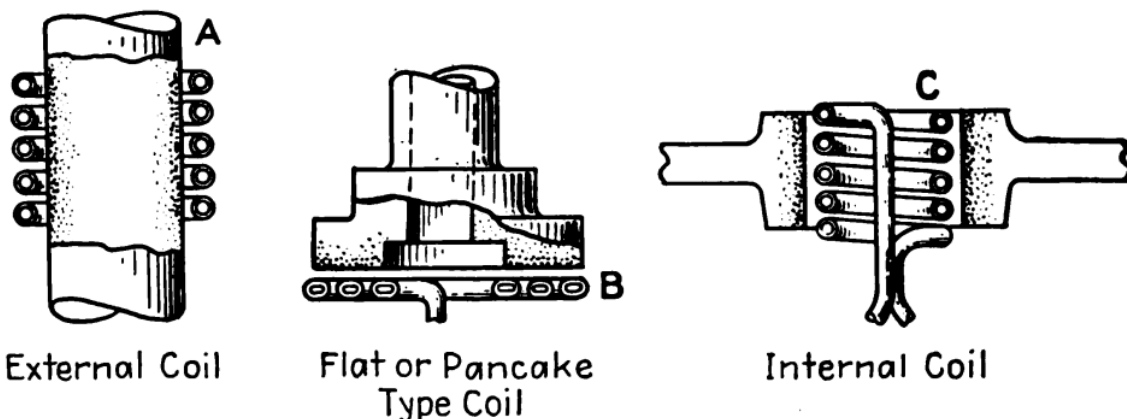
FIG. 42.—The three most popular types of multiturn coils are the external, pancake, and internal designs shown here.

For this reason outside surface-heating of parts, such as steel shafts, can be performed exceedingly fast. With a flat- or pancake-type coil, as at *B*, heating will be somewhat slower per square inch of area, or roughly 75 per cent that of the example

at *A*. With internal-type coils, like those shown at *C*, heat transfer is still slower, because less magnetic flux is concentrated on the work surface, and may be heated only 50 to 60 per cent as fast as outside heating. These estimates are based on the use of a high-frequency generator of a given output power. For non-ferrous materials heating times will be somewhat greater than for ferrous materials, usually in the order of $1\frac{1}{2}$ or 2 to 1.

Internal Coils. Since the density of the magnetic flux is less on the outside than on the inside of a coil, and because the greatest strength lies next to the coil, it is advisable to make
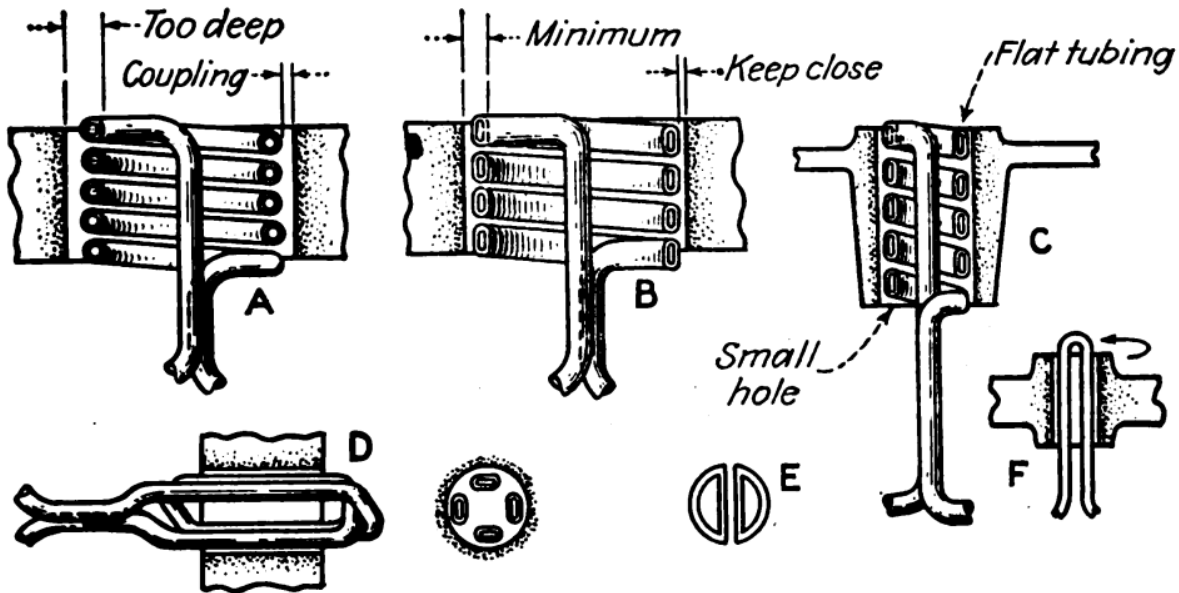
Fig. 43.—Constructional features of internal coils are shown here. Coils of this type should be made as thin as possible and should be located close to the work's surface.

internal coils in such a way that the over-all distance from the surface of the hole being heated to the inner surface of the coil is held to an absolute minimum. In *A*, Fig. 43, is shown a multiturn coil of usual design, which, when applied within a hole, results in the dissipation of heat energy because of the excessive over-all depth between the work surface and the inner diameter of the coil.

At *B* the condition is greatly improved, since the coupling between the work and coil is reduced and since the coil is flattened. This means that the over-all depth is held to a minimum, thus assuring maximum heat energy, the magnetic flux being more constricted to the heated area. The coupling for internal heating coils should be made no more than $\frac{1}{16}$ in., and less if possible.

Internal coils for hole heating usually are limited in size because of their mechanical construction, and usually a ⅝-in. hole is the smallest that can be heated with a multiturn coil, as shown at *C*. Another form of internal coil is the double-turn coil, illustrated at *D*, in which the tubing is flattened to provide for maximum heat transfer. . In making coils of this type, care should be taken to avoid closing in of the tubing, so that the water passage will not be restricted. Also, because the heat pattern within the hole is likely to resemble four longitudinal bands, the workpiece should be rotated during heating. The coil at *E* provides still another design using formed tubing, thus permitting the coil to be small in diameter.

The hairpin coil at *F* also is practical for small-hole heating, but the part must be rotated during heating to assure uniformity of heat transfer. Usually internal coils of the types shown are limited to surfaces in which the height of the heated surface is not more than twice the diameter. Where the length is in excess of this ratio progressive heating should be provided if possible. In this case the heat is concentrated to a small area of the hole, while the work itself feeds at a uniform rate, depending upon available output capacity of the generator, the size of the hole, and the area being heated.

When heating a tapered surface, the coil is usually made to conform with the taper, although exceptions may be considered as at *A*, Fig. 44, which shows a fixed-diameter coil arranged so that the pitch of the winding is wider at the large end than at the small end. With this design, a greater concentration of heat will be provided at the small end, because of the variation in pitch.

It is well to remember that with a fine-pitch coil the penetration of heat will be deeper than with one having a coarser pitch. Usually the spacing between coils should not exceed half the diameter of the coil, while smaller spacing is preferable.

In heating conical parts, such as bevel gears, a coil with a consistent spacing or coupling will result in a more intense heat at the small end, as shown at *B*. To compensate for this condition, the coil should be made with a wider angle at the small end, as shown at *C*, so that heating will be uniformly distributed.

The same procedure is followed when using a solid-inductor coil, shown at *D*. In heating flat surfaces, like that illustrated

at E, a coil made parallel to the face will have a tendency to create the greatest heat toward the center. Coils for such surfaces, therefore, should be made slightly conical or angular, as shown at F.
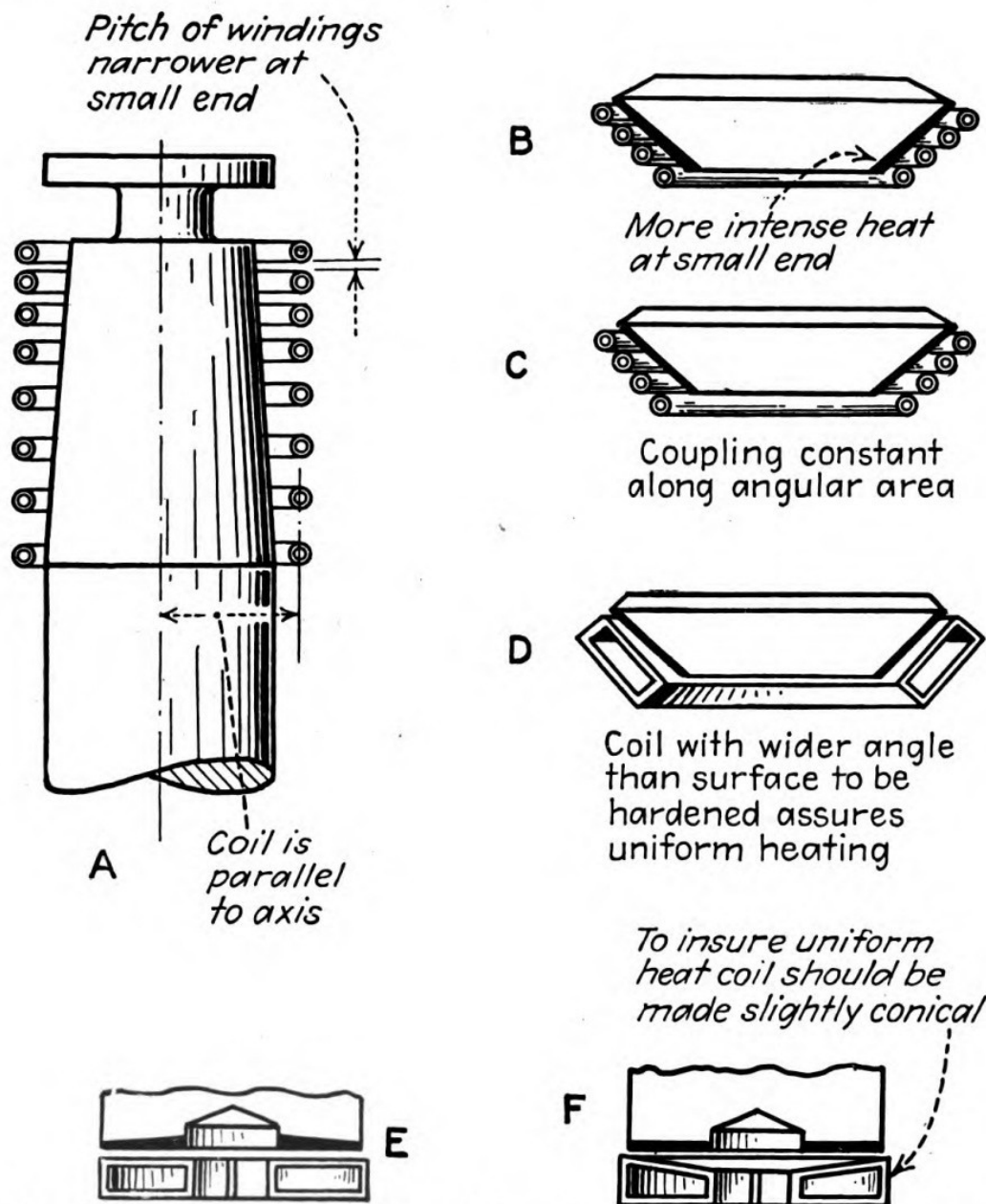

Pitch of windings narrower at small end

Coil is parallel to axis

A

B

More intense heat at small end

C

Coupling constant along angular area

D

Coil with wider angle than surface to be hardened assures uniform heating

To insure uniform heat coil should be made slightly conical

E

F

FIG. 44.—Coils provided with variations in spacings between turns can be arranged to transfer heat uniformly to tapered surfaces. Usually in heating tapered surfaces the coils should be made with a wider angle than that of the workpiece.

Distribution of Heat. An example of a multiturn copper-tube coil used for hardening a projectile on which differential-hardness readings are desired is illustrated in Fig. 45. The coil is made so that the hardness readings from the point of the projectile to

the base will taper gradually from 60 to 35 Rockwell C. In operation the part is heated and then quickly dropped into a quench. The variation in heat and hardness is attained by a variation in coupling, and in the pitch of the coil turns, which
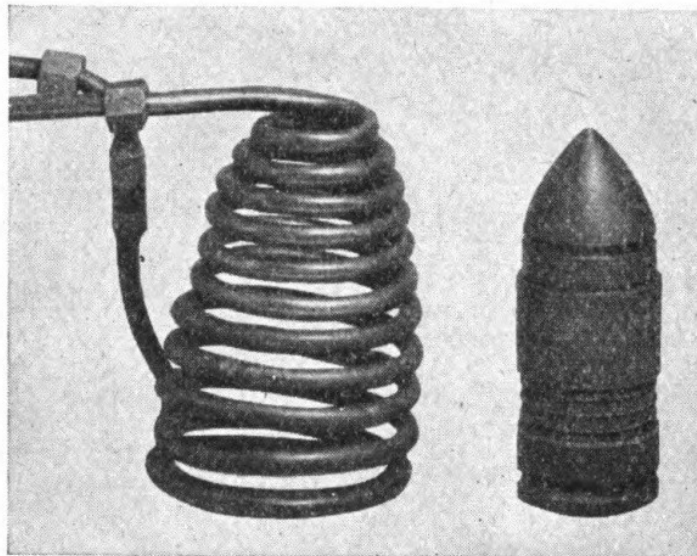
FIG. 45.—A coil provided with variations in turn spacings, which is used for the hardening of a projectile on which a gradient of hardness ranging from 35 to 60 Rockwell C. is obtained.

as can be seen are wider at the bottom than at the top. This type of coil provides for maximum heat where the hardest area is desired, and a gradual diminishing of heat for less hardness.
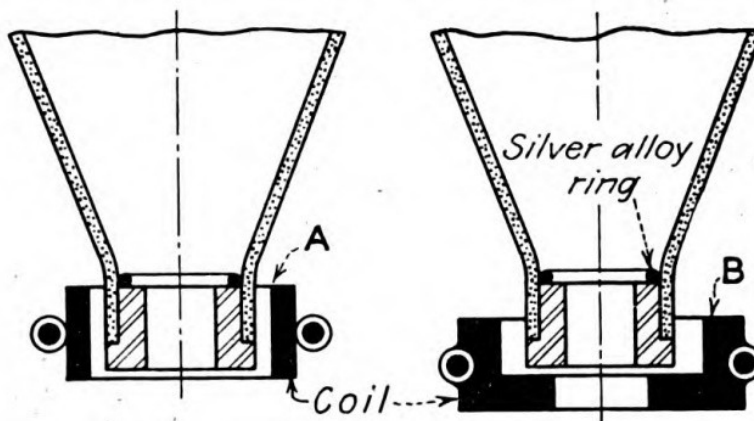
FIG. 46.—A single-turn heating coil used for brazing a steel tube and an insert together. It is necessary to arrange the coil so that the transfer of heat is concentrated on the heaviest section of the assembly.

In designing coils for heating purposes, it is often necessary to analyze the application to determine the best means of heat distribution. For the application shown in Fig. 46, which requires the brazing of a steel insert to a drawn-steel shell, the coil as shown at *A* might cause overheating of the thin material

before the proper amount of heat could be conducted to the heavier insert. This being the case, the outside surface also might blister and become badly warped.

To overcome this condition, a coil such as that shown at *B* would be desirable, since the generation of heat would be distributed more to the heavier section, particularly at the bottom, and then would travel by conduction to the remaining surfaces directly above. For heating operations of this kind, a solid inductor of the single-turn, or even-series, type, is to be preferred.
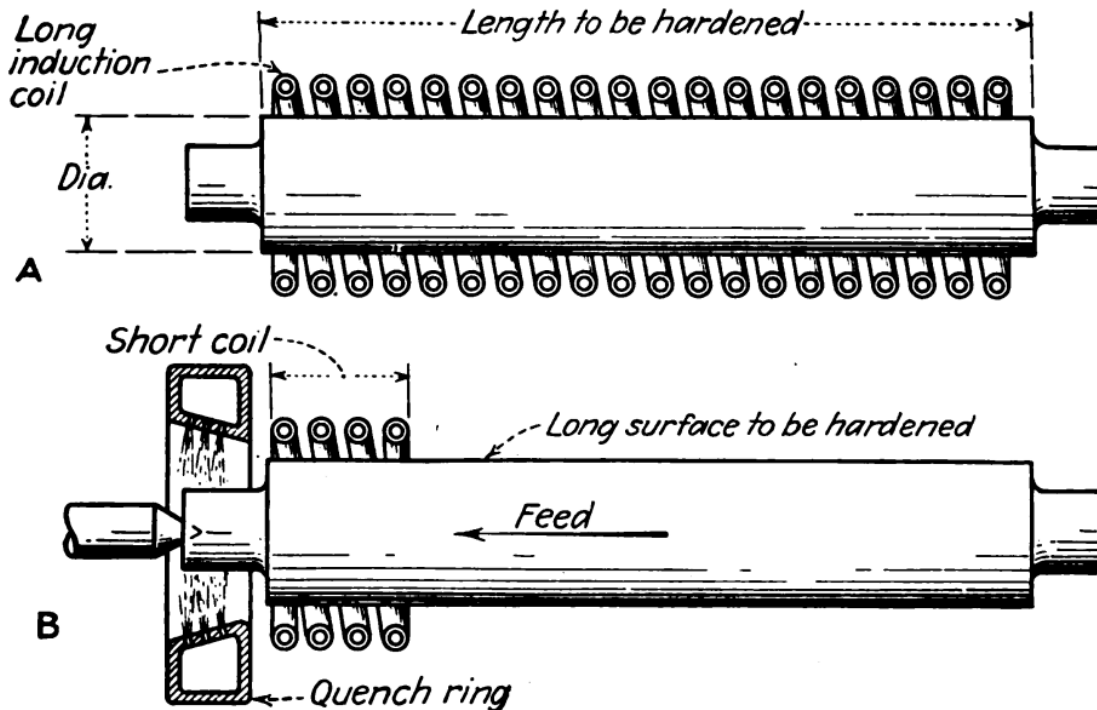
FIG. 47.—It is not good practice to make long multiturn coils, because uneven heating is very likely to take place. In heating long areas, it is better to use a short coil and feed the work progressively through it.

The coil can be made somewhat higher than might be necessary. Then after observation of the resulting heat the coil can be trimmed down one way or the other until the exact heat pattern has been produced.

Length of Coils. There is a limit to the length of surface which can be heated at one time, and while no fixed rule applies, a helical coil usually should not be more than three to four times its diameter, whereas a single-turn coil will be found more effective when the length is not more than half the diameter. The example shown at *A* in Fig. 47 obviously is too long, since too great a surface is being heated at one time, causing possible deflection as well as an uneven distribution of heat. For a

surface of this type, assuming that hardening is required, it would be much better to use a shorter coil and progressively feed the part through it, such as is shown at *B*. The available output power of a generator also is relative to the amount of surface that can be heated at one time. In this same example a generator with considerable power would be required to heat the entire shaft at one time, as compared with one of nominal power for the progressive-heating method.

Multiturn coils exceeding the proportions given can be used for the heating of thin sections, such as steel wire and rod, especially in annealing operations. For hardening and brazing require-
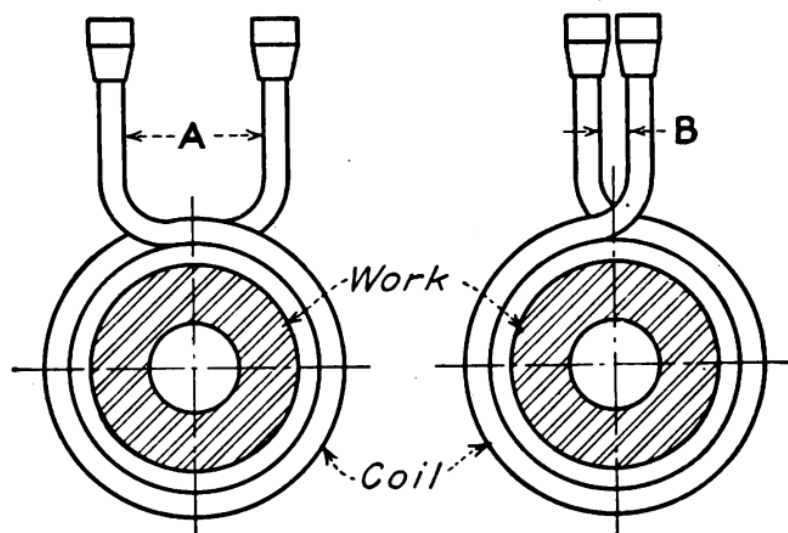
Fig. 48.—In connecting heating coils to generators, it is well to keep the leads as close together as possible in order to avoid inductance losses, which would detract from maximum heating in the work.

ments, however, exceptionally long heating coils may offer difficulties. Sometimes it is this consideration that decides whether a job can best be performed by inductive heating or some other method.

Inductance Losses. When connecting the leads of a heating coil to a generator, especially those of the quick-change type, it is desirable to keep them as close together as possible, in order to avoid inductance losses between the leads, as might be represented by the example at the left in Fig. 48. The spacing, as represented at *A*, would result in some dissipation of the high-frequency current, so that maximum heating of the work within the coil would not be attained. By providing leads as shown at the right, where the space *B* is held to a minimum, there is a better assurance of maximum heating of the work within a coil.

This same condition would be true in a series-connected coil, where substantial losses will occur if the proper technique is not provided. The coil shown at *A* in Fig. 49, for example, represents a very poor design, where owing to its shape undesired inductance is set up between the coil sections. On the other hand, the coil at *B*, which represents the same general type, is very well laid out and would offer the assurance of maximum heat concentration to the workpieces located in the openings.
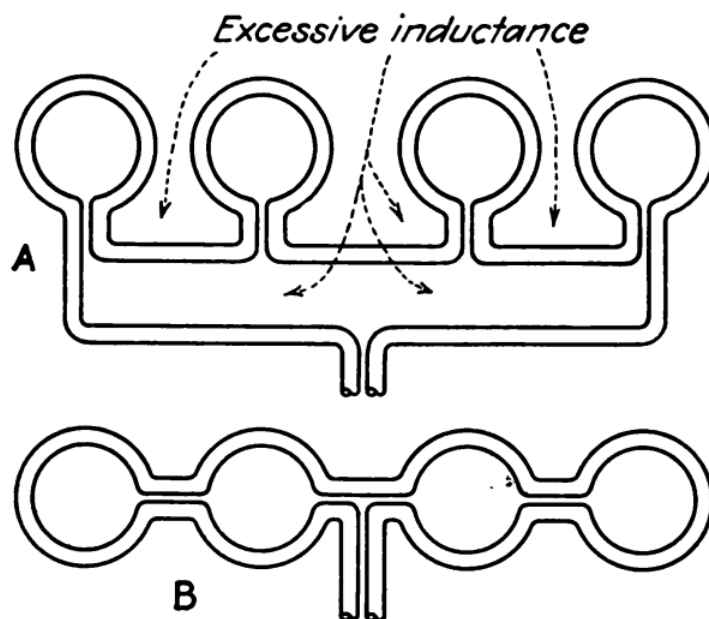

FIG. 49.—In connecting series-type coils, it is essential to make the connections in such a way that minimum inductance losses will occur.

Pitch of Coil Windings. In applying multiturn coils for the heating of steel shafts and other round parts, the pitch of the turn windings will have a direct relation to the depth of heat penetration. With a fine-pitch coil, such as that illustrated at *A* in Fig. 50, the magnetic flux penetration will be more highly concentrated on the surface of the work, with a resultant deeper layer of heat. With an open-pitch coil, where the space between windings is increased as at *B*, the penetration of heat to the surface of the work will be somewhat less affected by the fact that the magnetic flux spreads out over a wider area and causes certain losses. Usually in making multiturn coils it is best to arrange the windings so that the space between turns will not be more than one-half the thickness of the tubing itself. Beyond this limit, or with loosely wound coils, nonuniform heating is likely to occur, and unless the piece being heated is rotated the heat pattern on the work's surface will follow the spiral of the coil.

When a steel part, such as a shaft, is heated at a comparatively fast rate by a multiturn coil, there is likely to be a variation in temperature on the work's surface because of the field set up by the spiral windings.   The more open the windings of the coil, the more pronounced will be the bands of heat, to a point where the heated surface will follow the spiral form of the coil.   For this reason, the coupling, or spacing from the work to the coil is an important consideration and, likewise, bears a direct relation to the pitch winding of the coil.
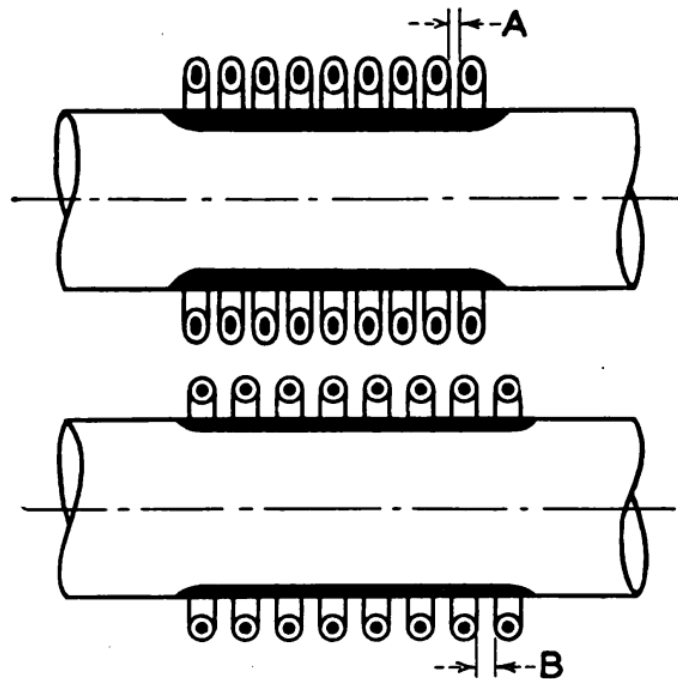
FIG. 50.—Coils provided with fine-pitch windings have a tendency to throw a deeper layer of heat than those wound with loose windings.

With a coil like the one shown at *A* in Fig. 51, where the coupling is close and the pitch winding of the coil loose, the heated zone will take on a bright and dark pattern, following the exact shape of the coil windings.   By increasing the coil coupling, as at *B*, the heating becomes more uniform, though it increases somewhat because of less flux-density transfer to the work's surface.

This heating effect is an important consideration when using multiturn coils.   It is most obvious when the spacing between coil turns is about equal to the coupling, and diminishes as the tube spacings are reduced, in proportion to coupling.   The best procedure is to rotate the work within the coil so that uniform heating is assured.   This can be done in many cases by hand, if

the part permits, or by a motor-driven spindle, using a speed as low as 25 r.p.m., or just enough to break up the uneven distribution of current density.
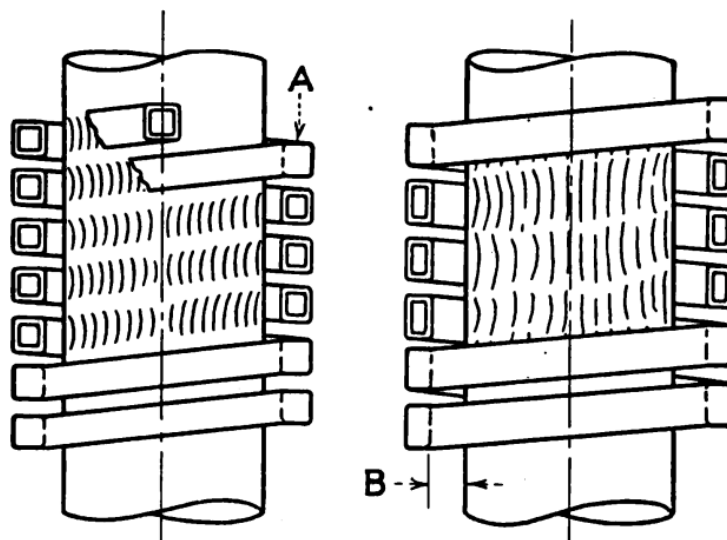

FIG. 51.—Multiturn coils should be correctly proportioned as to space between windings and their distance from the surface of the work, so that an even distribution of heat will be assured.

Naturally, the coil spacing around a part to be heated should be uniform, especially if a uniform distribution of heat is desired. In some cases, however, a slight amount of eccentricity between
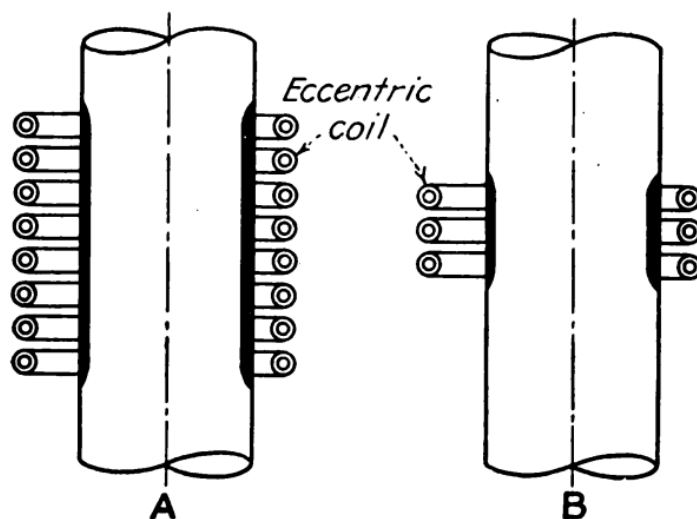
FIG. 52.—If an eccentric coil is used to heat a section of round steel, the variation in depth of heat penetration will be proportionately greater with narrow coils than with high coils.

the work and the coil is not objectionable and may have no effect on the heated area. This is usually the case when heating a small part and where an ample amount of power is available.

Where the rate of heating may be slower, however, eccentricity of the coil may produce a variation in heat, the side nearest the coil receiving the greatest amount.

With a high coil, like that shown at *A* in Fig. 52, a slight amount of eccentricity will be hardly noticeable. However, with a narrow coil, as shown at *B*, any appreciable amount of eccentricity or unevenness in coupling will be more apparent in the form of heat variations to the work's surface. This is quite noticeable in heating such parts as gears, especially when the thickness is small in proportion to the diameter. Rotation of
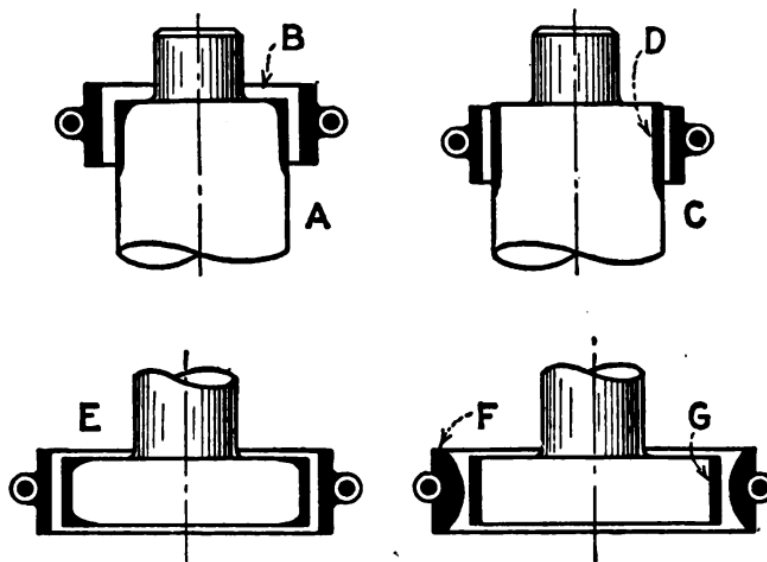
FIG. 53.—When heating coils overlap the edge of a piece of work, there is likely to be overheating on the end surface. Placing the coil slightly below the edge will produce a more uniform heat pattern.

the work, of course, offsets irregular heating due to slight variations in coil couplings, as would be the case with an eccentrically located inductor.

Heating Effects. When a cylindrical-type heating coil is placed around the end of a shaft in such a way that it projects over the edge, as indicated at *A* in Fig. 53, there will be a pronounced heating over the face as indicated at *B*. If, however, the coil is arranged as shown at *C*, in which case the edge is even with or slightly below the end of the work, the heat pattern on the surface will be more uniform, as shown at *D*.

This same condition exists when heating a disk, or the flanged area of a piece, as shown at *E*. The heat pattern will be such that the depth of penetration will be less in the middle of the blank than at the ends. With some parts it may be necessary

to use a formed coil, as shown at *F*, with the inner face made convex. This design provides for a uniform layer heat, as shown at *G*, and eliminates the overheating of the edges which might occur with a straight cylindrical-type coil. These same conditions apply to the use of multiturn heating coils.

In applying heat to a surface which may have a shoulder or flange at each end, as illustrated in Fig. 54, the spacing of the heating coil in relation to the various surfaces becomes an important consideration. If the coil were proportioned as shown at *A*, where the edges of the coil are closer to the flanges than the
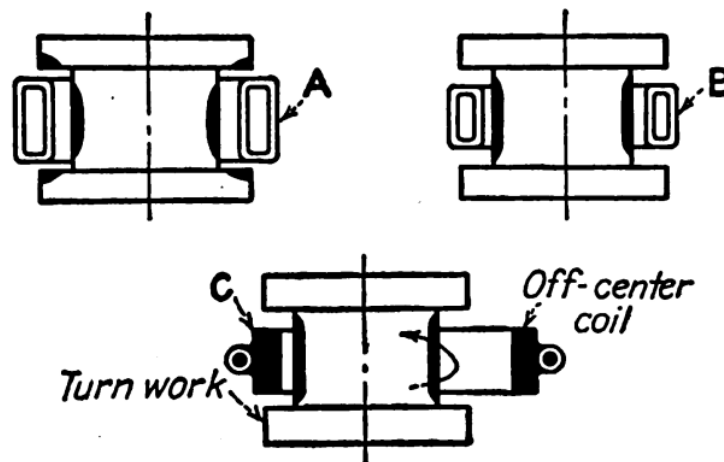
FIG. 54.—In applying heat to flanged surfaces, the relationship of the coil to the surface of the work is an important consideration.

central part is to the body, some heat would be applied to the edges. This would result in the absorption of much of the flux density, so that the body of the part would receive only a small amount of heat.

For such a surface, therefore, the coil should be made as shown at *B*, arranged so that the coil is closest to the body requiring heat. In any case, a split-type inductor would be required in order that the heat-producing surface might be properly placed in relation to the surface requiring heat. For such a part there is the possible use of a larger coil such as shown at *C*, through which the work is inserted, and then positioned eccentrically as shown. Rotation of the work is thus provided. With such a setup the flanges are more liable to absorb some of the eddy currents, although the body will become more predominantly heated.

Two-piece Coils. A split-type coil like that used to heat a part having flanges on each side of the bearing surface is illus-

trated in Fig. 55. In each section of the coil are separate cooling tubes, which in turn are series connected for the continuous flow of water. Both sections are held together by a clamp, although various other means of connecting may be used. One of the pieces to be heated is shown at the right of the coil.

A hinged-type inductor of solid design used for the hardening of crankshaft bearings is illustrated in Fig. 56. The coil is
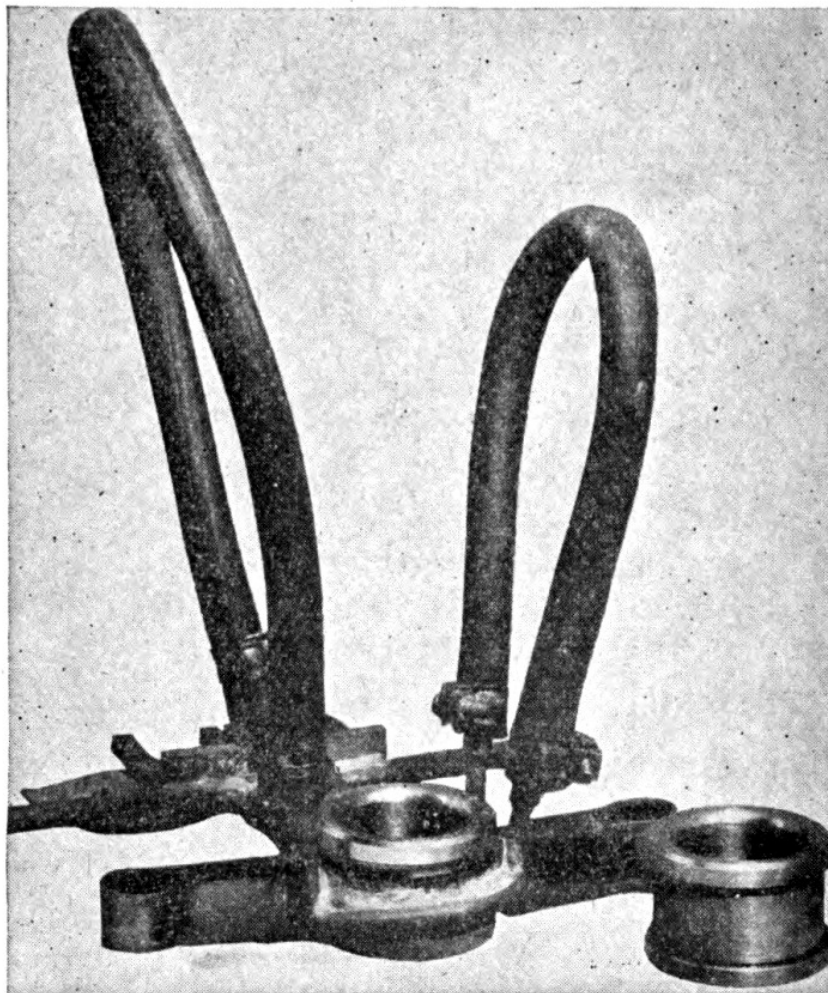

FIG. 55.—A typical single-turn heating coil of the split type, which is used to heat the small diameter of a flanged part.

arranged so that after the work has been properly located and centralized within it, the upper half of the coil is brought into contact with the lower half, thus completing the electrical connection. Both coil sections are held together with pressure during the heating operation. Also, both sections of the coil are provided with internal passages for cooling purposes, with suitable quenching chambers to make the quenching water pass directly through the area of the coil's heating surface. The cycle for the

operation is controlled by a timer and functions as follows: (1) the coil is closed; (2) high-frequency heat is generated to the work's surface; (3) the quench is applied; and (4) finally, the coil is opened so that the work can be removed.

When applying high-frequency current to surfaces which include keyways, or holes like those illustrated in Fig. 57, the eddy currents concentrate at the corners, probably causing some over-
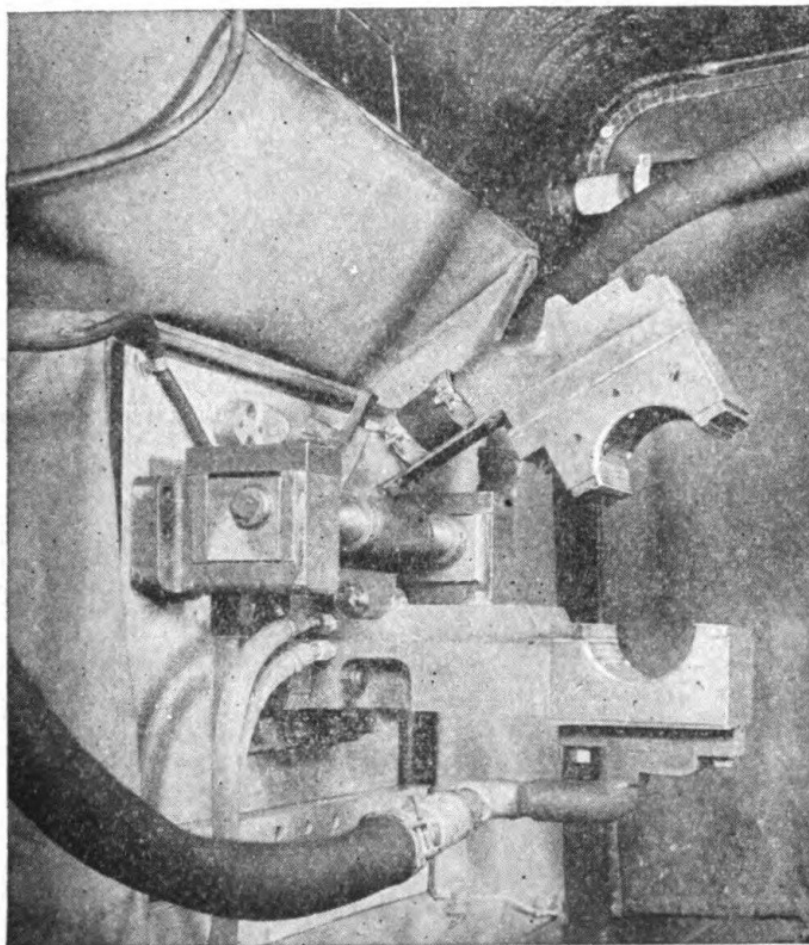
FIG. 56.—A well proportioned hinged-type induction-heating coil used for hardening crankshaft bearings. (*Courtesy of The Ohio Crankshaft Co.*)

heating. With the keyways as shown at the left, the edges will heat rapidly and a slight burning action might take place. To overcome this, the part can be fitted with a copper key to bridge this gap, thus making the heating more uniform.

In case a part having a hole through the surface is to be heated, as shown at the right at *A*, the magnetic flux from the coil will tend to enter the hole and develop maximum heat around the edges. To reduce this condition the hole can be provided with a

copper plug which shunts the opening and thus reduces the absorption of eddy currents at this point.

In heating a slotted part within a cylindrical coil, as shown at *A* in Fig. 58, the circulating current on the surface of the work-
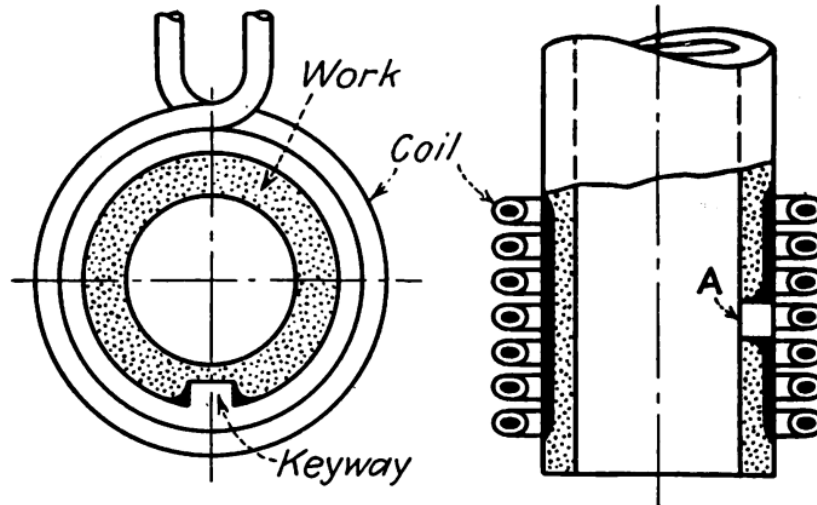
FIG. 57.—Overheating of sharp corners, such as keyways and holes, often takes place and the use of copper inserts may be advisable to shunt the path of high-frequency current.

piece naturally is interrupted by the slot, but the current will continue to flow on the inside because of the nature of high frequency, which must form a closed circuit. When treating
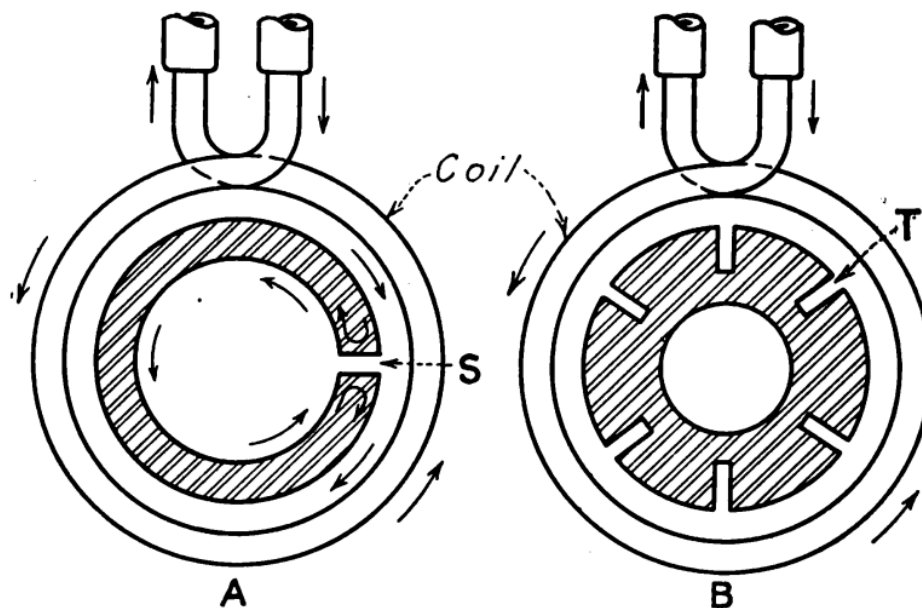
FIG. 58.—In heating shaped parts such as those shown in this example, the high-frequency current tends to crowd into the slots resulting in overheating.

parts of this design, therefore, a somewhat higher heat usually is produced at the edges of the slot, as indicated at *S*. With the multi-slotted part as shown at *B*, the circulating current around

the workpiece will have a tendency to crowd into the slots T, and again an overheating condition is most likely to occur on the corners. The thinner the coil in relation to its diameter, the more pronounced the heating at the slots. On the other hand, with the use of a heating coil having a height greater than its diameter, this condition will be less pronounced.

Single-turn Coils. Solid-type induction coils are made of sheet copper, as illustrated in Fig. 59, and can be arranged for single or multiple operation. The coil shown at A, which is
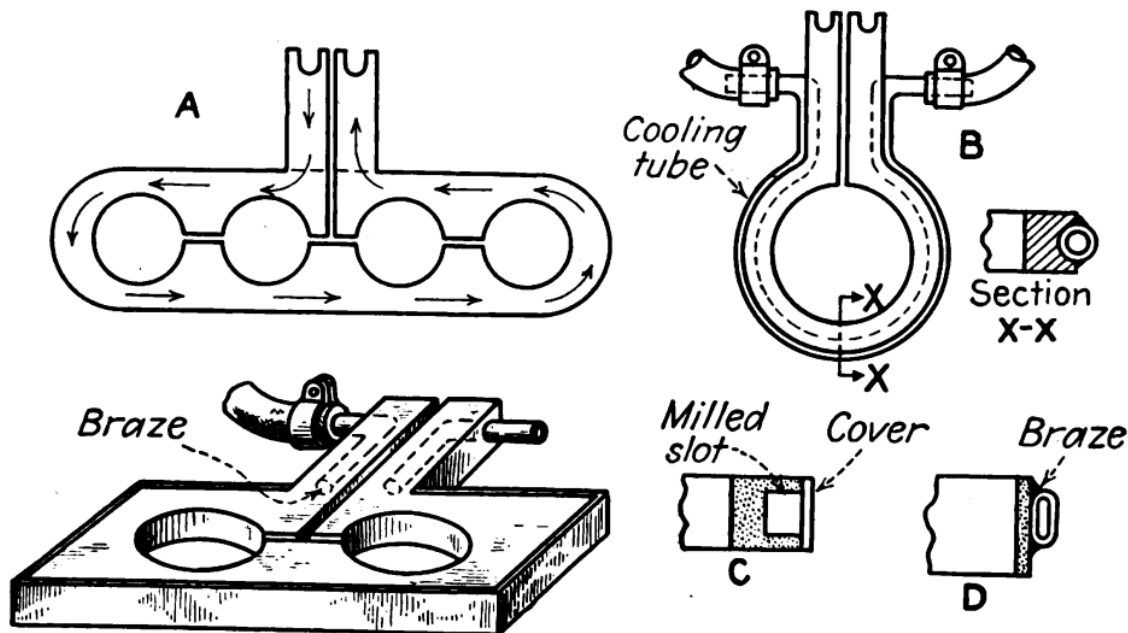
FIG. 59.—Constructional details of single-turn coils made from flat copper plate and provided with means for cooling.

typical for heating parts simultaneously, is made of a thick copper plate, bored to provide coupling sufficient for the diameter. Two connecting blocks are brazed to this plate, and then the plate is sawed out, as shown, so that the high-frequency current will follow the path of the arrows, coming in at one block and going out at the other.

At B is a single-station coil of similar design, showing a suitable method for providing the necessary cooling. A groove is milled around the coil, and a copper tube is brazed in place. At C is shown another solid-type inductor, in which the cooling chamber is provided by milling a slot around the outside edge and brazing a sheet-metal cover over it. The water outlet to the two connectors is made by drilling a hole through them and connecting a small tube, as shown. Another type of solid inductor is illus-

trated at *D*. This includes a band of copper to which a section of flattened tubing is brazed to the outer edge.

In making the so-called solid-type inductors, which comprise a single-turn coil, it is best to consider the proportions shown in Fig. 60. It will be seen that the h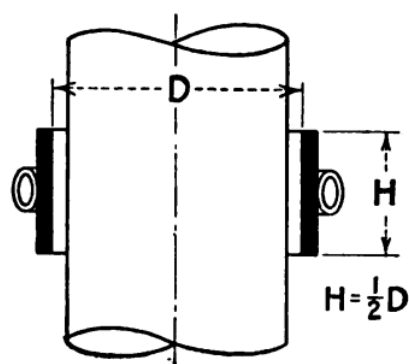eight of the coil is equal to one-half the diameter. These proportions can be exceeded in certain cases and various modifications are possible, but it is usual to limit the use of solid inductors to applications in which the height or length of the heat zone is less than the diameter of the coil. When a longer area requires heating, multiturn coils may be used to better advantage. If the area to be heated is exceptionally long, progressive feeding may be the solution.

FIG. 60.—In making single-turn coils it is well to keep the over-all height to approximately one-half the diameter as shown.

The length of the heated zone of a shaft placed within a cylindrical coil will usually exceed the over-all height of the coil at both ends by a distance equal to the coupling *C*, as shown in Fig. 61. This overlap is indicated at *E* in the illustration. When the thickness of the coil *T* is increased, as shown at the
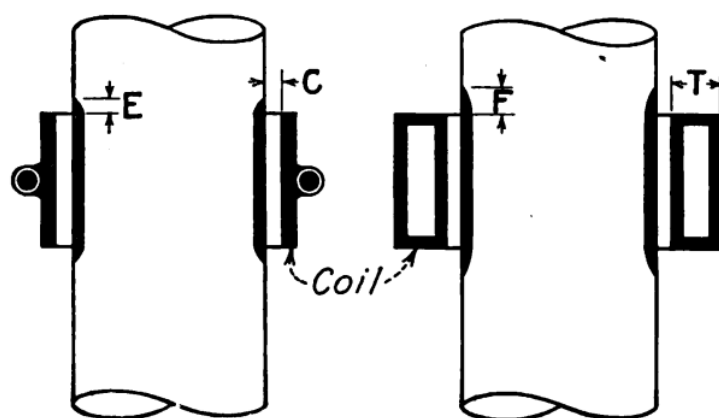
FIG. 61.—The over-all length of a heated area increases slightly as the thickness of the coil is increased.

right, there is a tendency for the heating zone to spread out still farther on each end of the coil, as indicated at *F*. This heating action is the result of a wider distribution of magnetic flux, which develops from a thicker heating coil. The same condition also exists in either case, when using multiturn copper-tube heating coils.

Series-type Coils. The coil illustrated in Fig. 62 is used for heating the inner surface of a rocker arm which requires hardening. The coil comprises two turns positioned so that they lie adjacent to the surface requiring heating.

A good many applications of induction heating require the use of coils which might have two or more windings spaced widely apart to suit surfaces of varying size. In this case it is important that the paths of the current flow in the same direction. Assuming that a double-turn coil is desired, like that shown at *A* in Fig. 63, the winding arrangement should be such that the current flows in the same direction, as indicated by the arrows. If a coil were made such as that as shown at *B*, with the current flowing in one direction in one coil and opposite in the other, the magnetic flux of one would have a tendency to cancel that of the other, so that practically no heating would result. This is an important consideration in the construction of coils of this type, particularly where multi-turn and series-type heating coils are needed.

FIG. 62.—A small copper-tube coil arranged to heat two parallel inner surfaces of a steel arm which requires hardening on the face only. (*Courtesy of Federal Telephone & Radio Corp.*)

A multiturn coil of the series type arranged for hardening two surfaces is illustrated in Fig. 64. While applications of this type can be provided for as shown, there are bound to be some losses due to the length of the leads between each coil section and, before the adoption of multiple heating as illustrated, the advisability of hardening the surfaces separately should be considered. In any case, a coil of this type should be so arranged that the leads are close together and never as indicated by the dotted lines, for the inductance resulting from the jumper and the input leads which would cause heat losses.
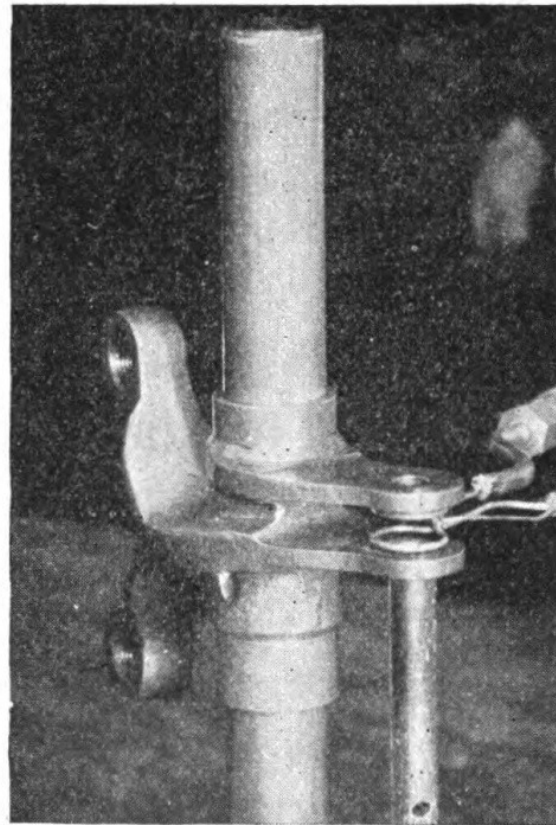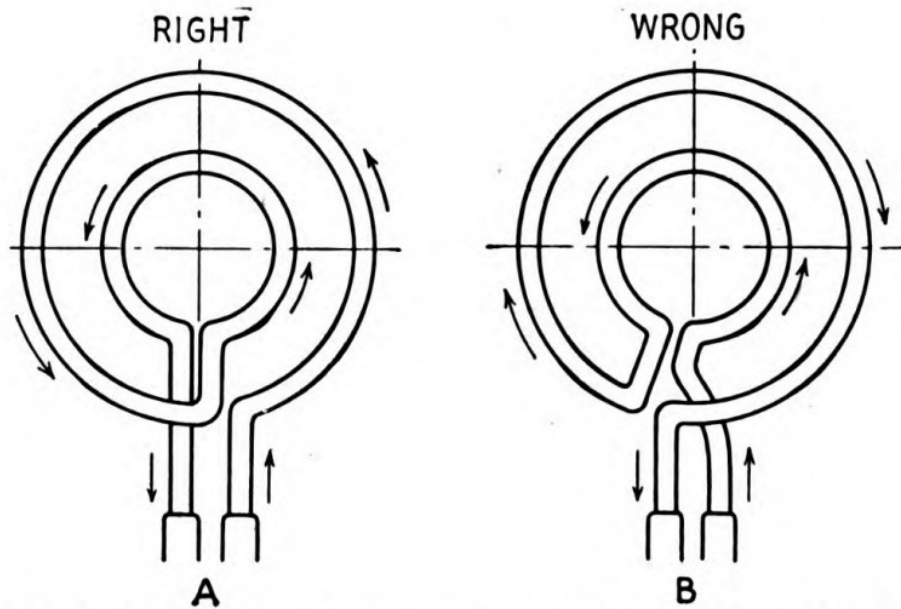
Fig. 63.—When making series-type coils, particularly those of the flat type, it is essential that all turns be made to carry the current in the same direction, as shown at the left.
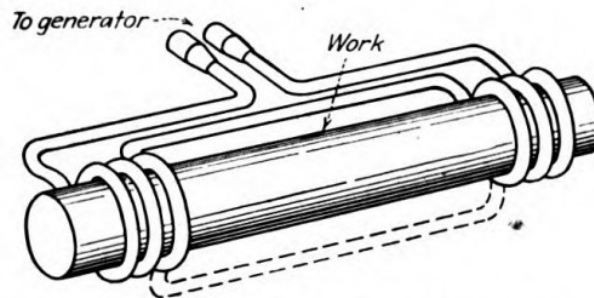

Fig. 64.—In constructing a series-type coil as shown here, it is important that the leads be kept close together in order to assure maximum heating to the areas on which heat is required.
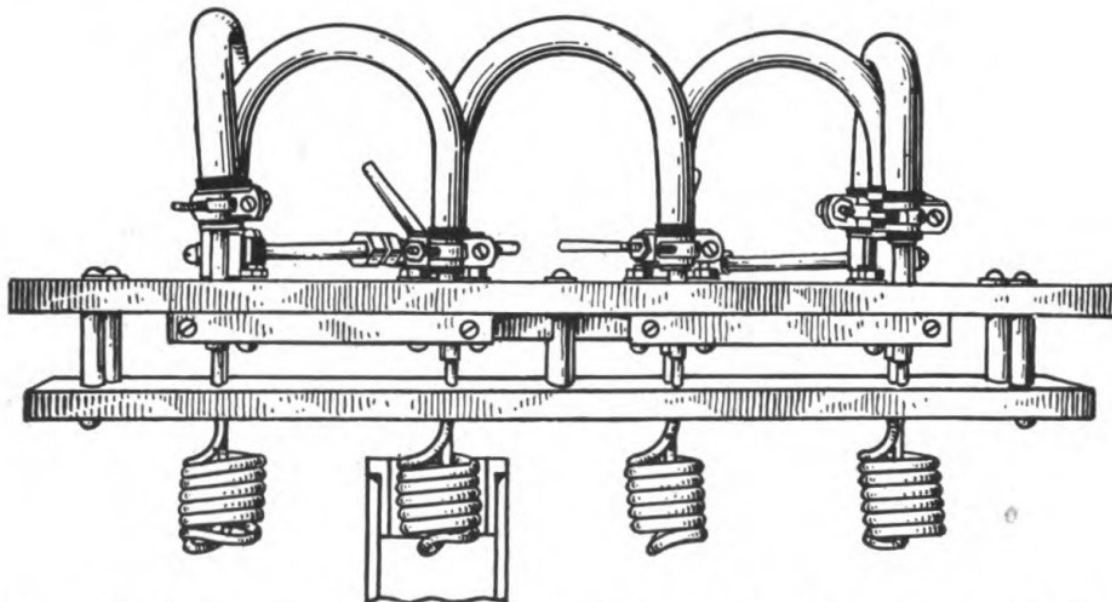

Fig. 65.—A series-type coil assembly, comprising four multiturn coils, arranged for internal heating.

Multiturn copper-tube coils of the series type can be made of a single piece of tubing, as has been shown, whereas another practical design is that shown in Fig. 65. Here the coils are made separately and joined together by bus-bar jumpers, or connectors. The hose shown at the top is used for providing a continuous flow òf water through all four coils. The two supporting members, through which the copper tubing is assembled, are made of asbestos board.

In Fig. 66 is illustrated a series-type internal-heating coil showing another means of making a connection. Each coil is
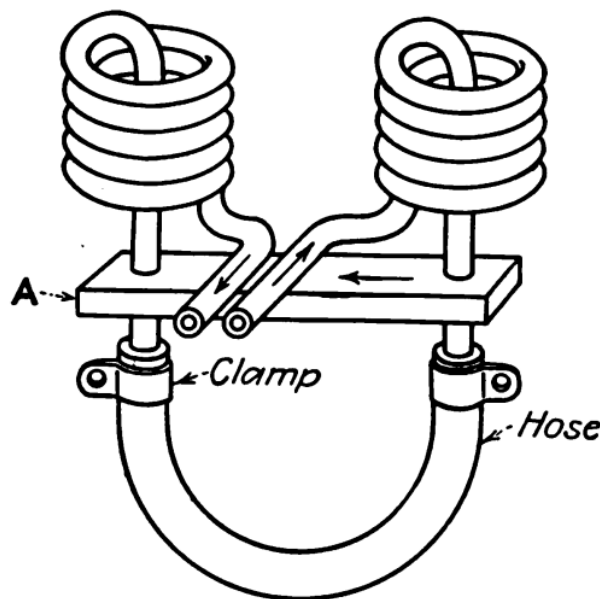
FIG. 66.—Double-type internal-heating coils arranged with a bus-bar connector and a hose for the continuous passage of water.

made separately and then connected to a jumper plate *A*, through which the high-frequency current passes from one coil to another. The ends of the coil tubing are then connected with a section of hose, to provide continuous passage of cooling water. The other two ends of the coils are connected to the output leads of the high-frequency generator. This design can be used for a greater number of coils, which may have to be joined together and, where operating conditions permit, operated in series.

A multiturn coil used for brazing together two steel sections in which heat is desired from the inside surface is illustrated in Fig. 67. The part at the right has been cut in half to show the relative location of the coil. When long leads are required, as is true in this case, it is necessary to keep the leads close together, particularly where they enter the bottom opening, like that

shown.   It must be remembered that if the leads lie adjacent to a metallic surface, they will generate heat where it may not be wanted and dissipate some of the energy needed for a particular portion.   In this case, the leads are mounted in insulating blocks attached together but separated by mica insulation.   For the operation shown, the two pieces are handled in one setting and the two coils are series connected.   All lead connections are made on the underneath side of the table.
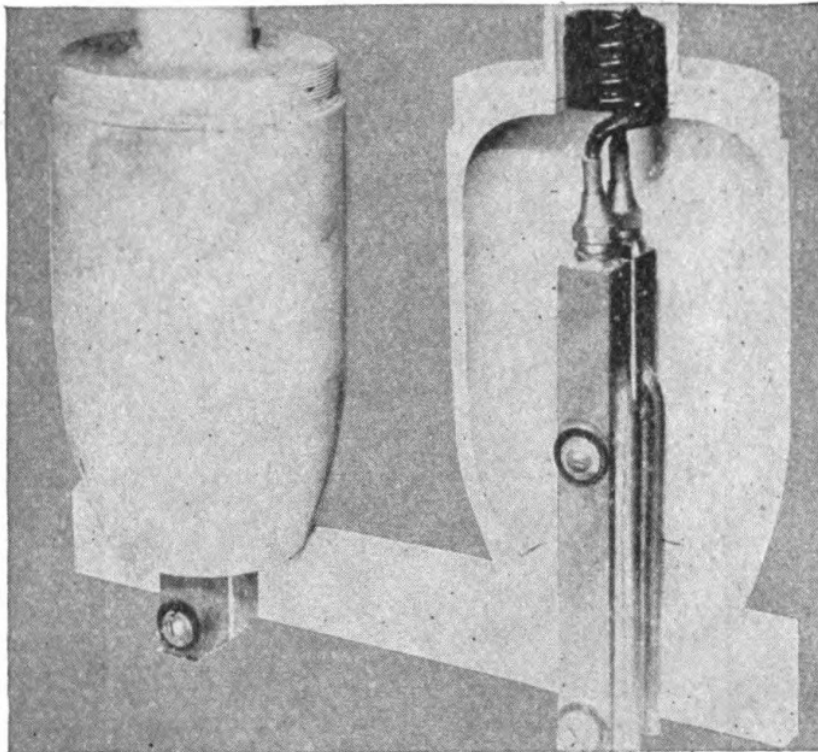

Fig. 67.—A series-type internal-heating coil with two separate coil units, which is used for the brazing of two steel cases simultaneously.

The coil shown in Fig. 68 is an excellent example of a solid-type inductor for heating two parts at one time.   The coil is made from a plate of copper $\frac{3}{8}$ in. thick and bored out to provide suitable clearance around the two workpieces to be heated.   The copper tube, used for cooling, may be seen around the outside edge of the coil.   The coil is supported by two angle plates connected to the front panel of the worktable.   Since the panel is made of insulating material, the brackets have no means of shorting the high-frequency current.   When making supports for coils it is important to provide proper insulation.   The coil is used for brazing two steel tubular parts together, like those shown at the right.

A series-type coil made from several copper bushings attached together is illustrated in Fig. 69. Around the upper and lower
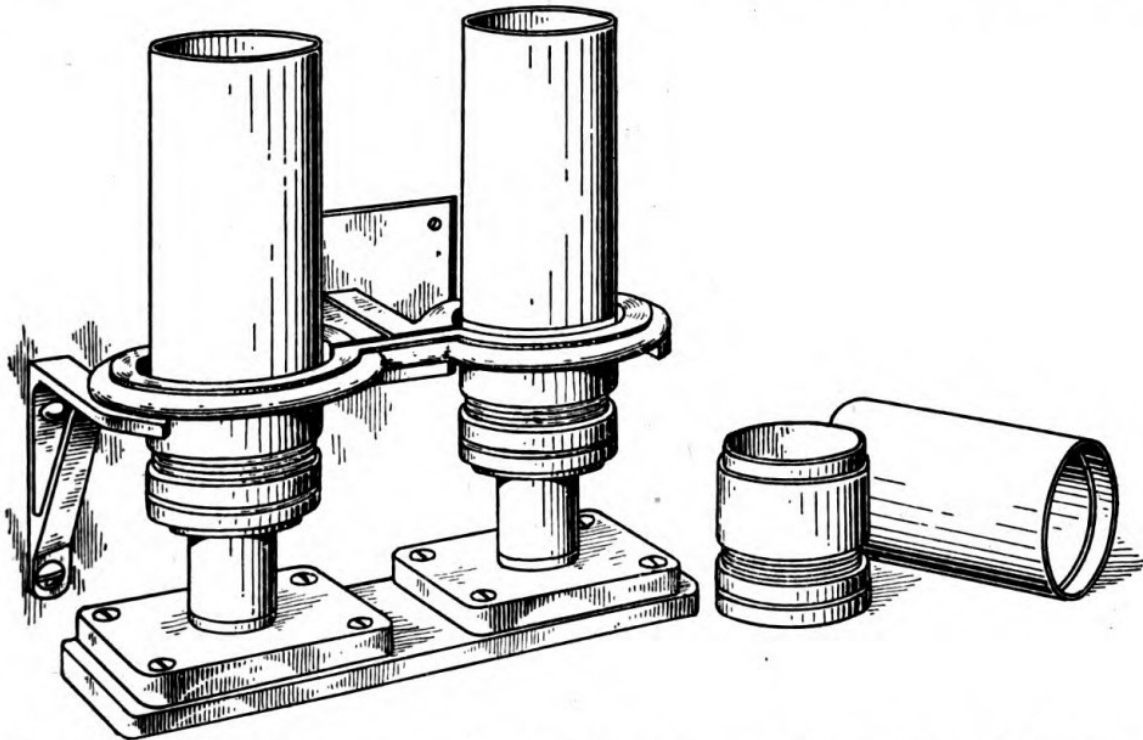

FIG. 68.—Tandem-design heating coil of the single-turn type used for the brazing of steel-tube assemblies.
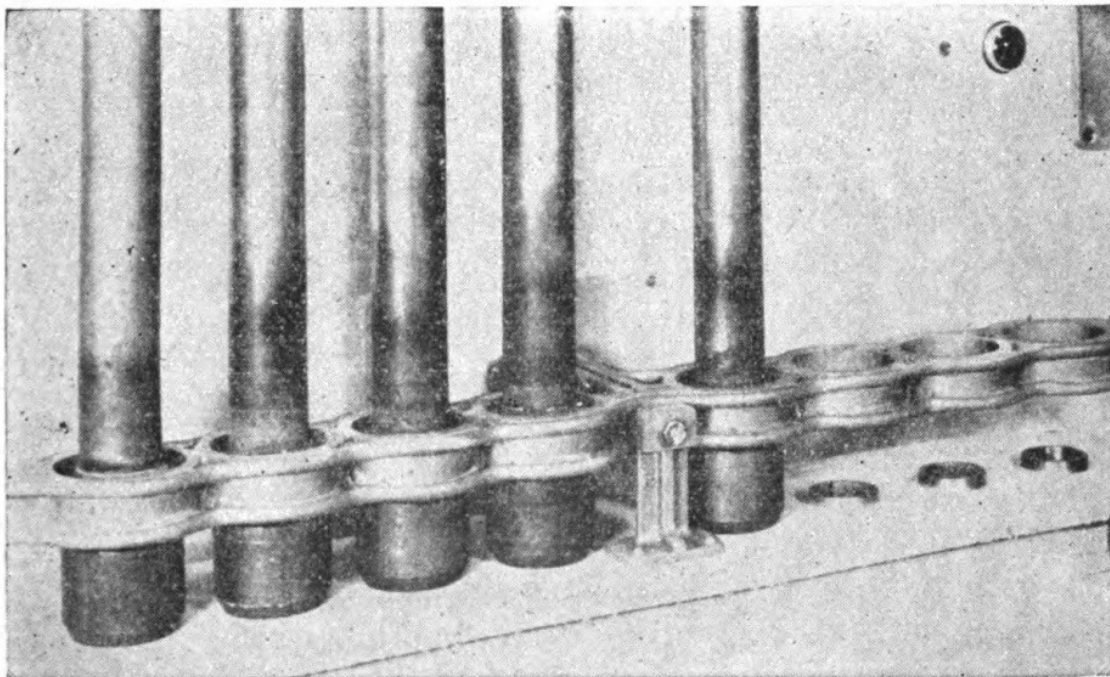

FIG. 69.—A series-type heating coil made from a series of copper bushings, arranged to handle eight pieces simultaneously, is illustrated here. (*Courtesy of Induction Heating Corp.*)

portions of the bushing are brazed the copper tubes used for cooling. Saw cuts are provided between the bushings in order

to provide for a continuous path of high-frequency current. The operation in this case is the brazing of a steel tube to a cap. The coil and fixture are arranged so that eight parts are completed simultaneously. A coil of this type is relatively easy to build and may be employed in a variety of operations requiring multi-setups.

The same general principle is applied to series-type coils made from a flat copper plate, like the one illustrated in Fig. 70. Here the cooling tube is brazed on the underneath side of the plate and shaped to conform to the coil openings. The tubing
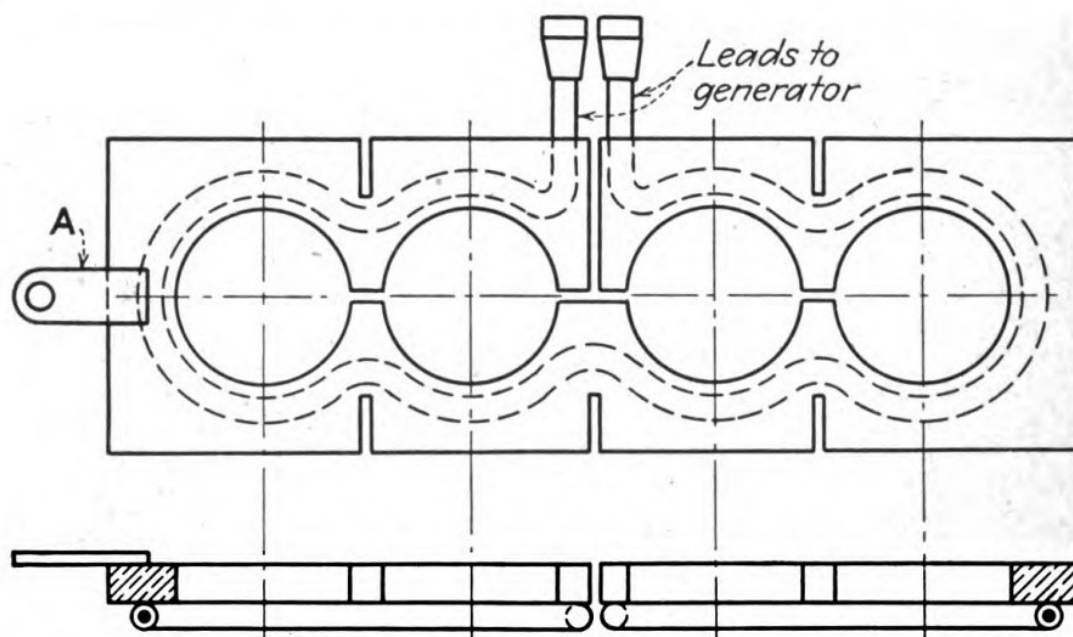
Fɪɢ. 70.—A heating coil made from a flat copper plate and provided with a cooling tube, placed on the underneath side, is illustrated above.

connections are brought out at one side, to provide a suitable connection to the output leads of the generator. The coil is provided with small end plates, as at *A*, to which supporting braces can be attached, to provide for a rigid mounting.

General-type Coils. The heating path, or area of surface contact, can be increased by means of a flat disk brazed to a copper-tube coil, as illustrated in Fig. 71. When the heating area desired is greater than can ordinarily be obtained by means of a single-turn copper-tube coil, this method can be well applied. It is possible, of course, to use a multiturn pancake-type coil in place of the single-loop coil illustrated, but usually the application of a wide heating disk on a single-turn coil, as shown, will result in a more even distribution of heat to the work's surface. The same principle can be applied to series-type coils as well as

step coils, in which a coil of smaller diameter may be located within another of larger diameter.

Another form of single-turn inductor for internal heating is illustrated in Fig. 72. The coil comprises a copper ring A, which is slotted as shown. A groove then is milled around the
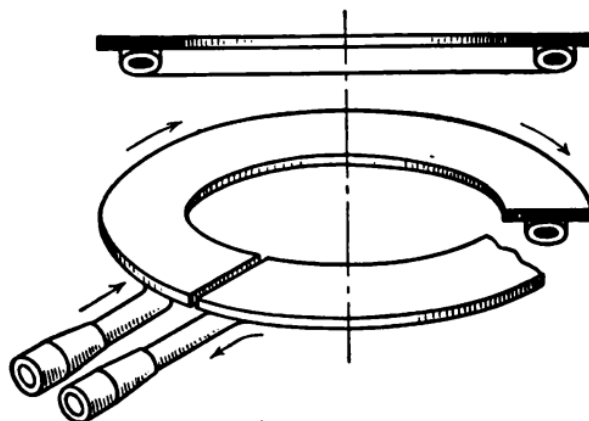

FIG. 71.—A convenient way to increase the heating area of a single-turn coil is to attach a flat plate to it, as shown above.

top face, as shown at B, after which the cover plate C is assembled. The leads D are then connected to the under side of the ring. A section through these connections is shown at X.

A coil of this type has many applications, and often the general principle of the design can be arranged for the heating of restricted areas. The leads can be readily connected to the outside, if desired, so that the coil can be used for external heating.

Such a coil for the heating of a small stud is illustrated at A in Fig. 73. A section is shown at B. This type of coil can easily be connected in series so that several areas will be heated simultaneously. At C is shown another modification of this design. Here the coil is formed out to localize heat at the base of a stud.

FIG. 72.—Constructional details of a solid-type inductor with an internal cavity for the passage of cooling water.

A coil of this type can be arranged to heat hard-to-get-at corners and, since it is made of a solid ring, remodification is possible, by machining of some kind, should slight changes be required to produce a certain heat pattern.
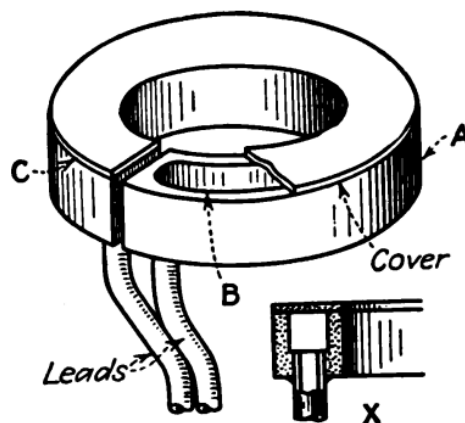
An example of this type of solid-inductor coil, connected in series, is illustrated in Fig. 74. It is applied for the brazing of two flanges to the outside of a tube requiring inside heating. It will be seen that the high-frequency connections are arranged so that the current circulates in both coil sections in the same
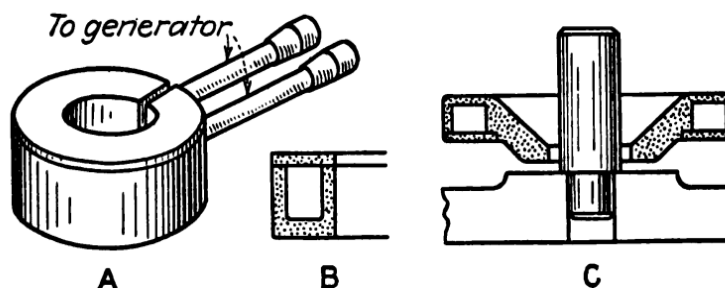

FIG. 73.—A representative design of solid inductor, which can be made with various modifications to localize the transfer of heat to restricted areas.
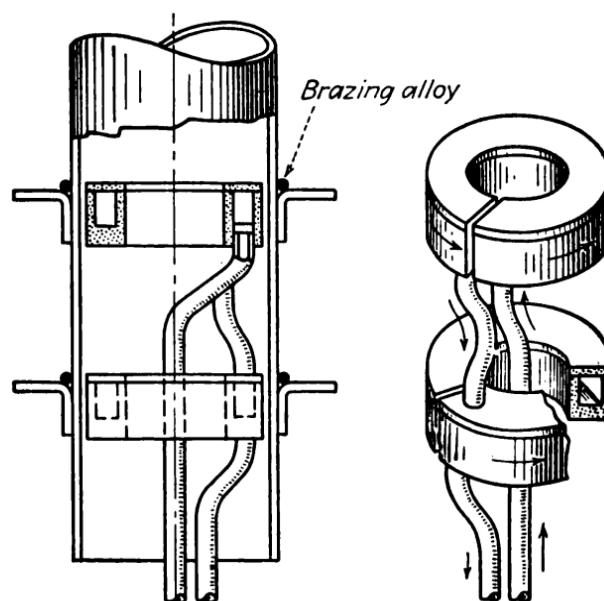

FIG. 74.—A series-type heating coil for internal heating is illustrated above. The coil sections are connected, so that the current flows in the same direction in both coils.

direction, as indicated by the arrows at the right. A coil of this type will provide uniform heat to both areas, while the copper-tube connections are formed back toward the center in order to avoid unnecessary heating on the surface of the tubing between the joints, where heat alone is required.

A modification of this coil is shown in Fig. 75. Here the construction comprises a slotted copper sleeve, as at *A*, on the

inside of which is brazed a single copper tube *B*. This provides for the passage of the cooling water to the generator leads as well as for the connections between coil units. This series-type coil is arranged for heating two surfaces of different diameters, and is for internal heating, such as the coil shown in the preceding example.

Parallel Inductors. High-frequency current will circulate around the surface of the metal part even though this is not completely surrounded by a coil. Naturally there are limits in the extent to which this principle can be applied, but for average small parts, usually requiring high-frequency heating, it is possible to use two parallel inductors and to pass the work underneath, or arrange it in approximate relation to the
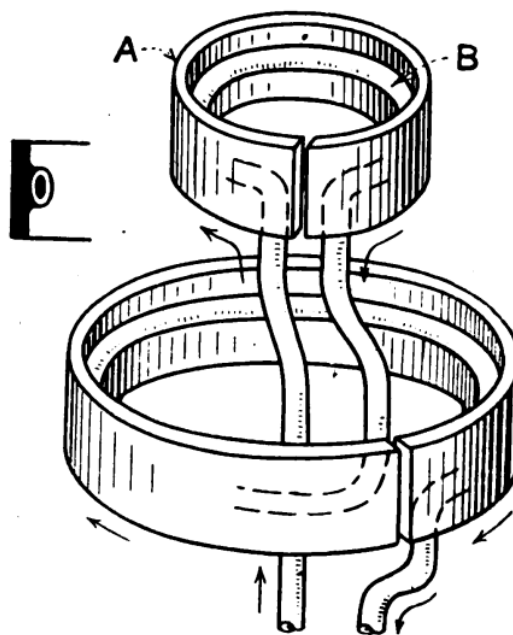

FIG. 75.—Another form of series type internal heating coil. Copper tubing is used for connecting both sections, as well as to provide for the flow of cooling water.

inductors, so that heat will be absorbed around its entire outer surface. This principle is illustrated in Fig. 76. Here, at *A* may be seen the relation of two parallel inductors used for soldering a
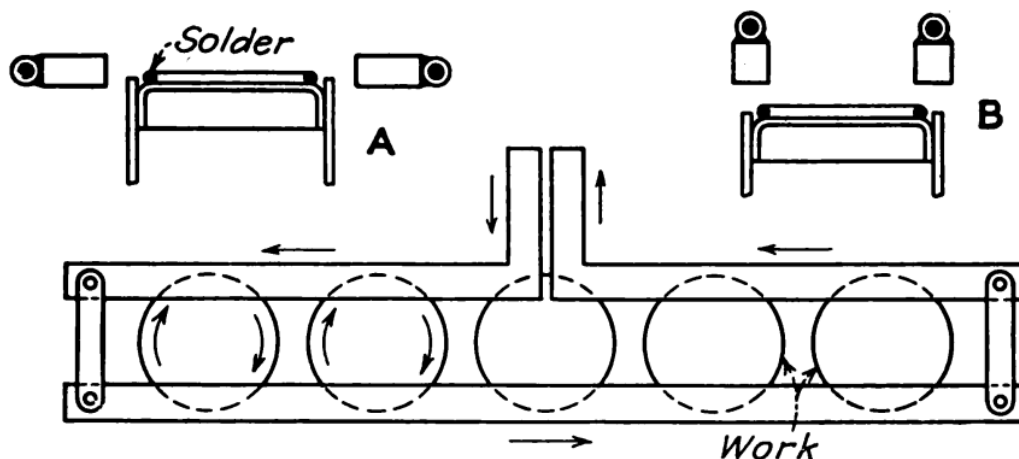

FIG. 76.—An example of a parallel-type inductor, comprising two bars, which is used for the soldering of condenser cans.

cover plate to the body of a round condenser can. In this case the heat is concentrated to the edges only. For the example shown

at *B*, the inductor bars are located directly above the joints to be soldered, which in some cases will be found preferable.   The principle of heating is shown below.   It will be seen that the high-frequency current circulates through the bars of the coil which, in turn, is induced into the work located underneath in the opposite direction.   In handling operations of this kind, the work can either be placed in a fixture that provides correct relation to the inductors, or conveyor-fed progressively under the inductors.

Another form of inductor, comprising two bars, is illustrated in Fig. 77.   Here the longer bar *A* is adjustable by means of the jumpers *B*.   As will be seen, the bars are provided with cooling
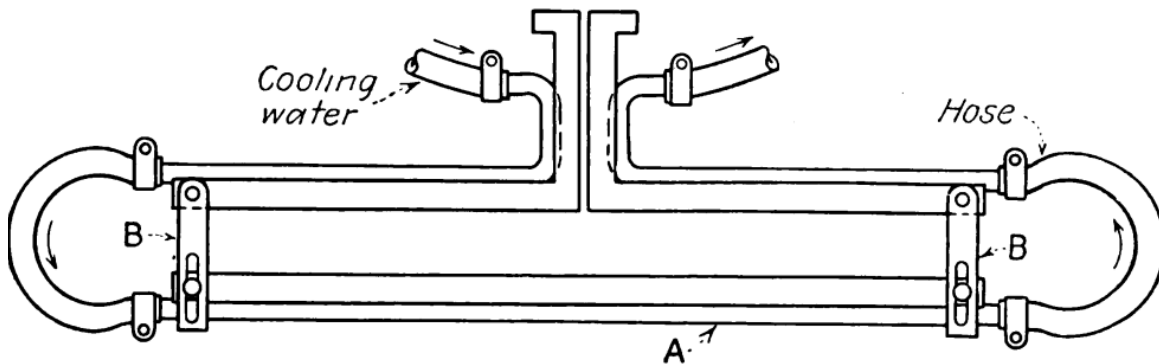
FIG. 77.—A two-bar parallel inductor of the adjustable type is shown above.

tubes and have hose connections at their ends for the continuous passage of cooling water.

The coil shown in Fig. 78 also is of the two-bar type and is arranged so that work can be passed through the opening, as illustrated at *A*.   The part represents the end of a drawn-steel shell which requires annealing.   The operation is performed by feeding and rotating the work through the bars, starting at one end and leaving at the other.   In mounting coils of this type, it is necessary to provide suitable supports, such as stand-off insulators, in order that a rigid mounting can be obtained.

In Fig. 79 is illustrated a two-bar inductor of the parallel type used for the heating of a long steel bar requiring hardening at one edge only.   In this example the inductors are cut out to conform to the shape of the part, as shown in the cross-sectional view at *A*.   Holes are drilled lengthwise through the inductors for the passage of cooling water.   At one end a jumper is provided, whereas at the other end of each bar the terminals connected with the generator are brought out.   Coils of this type can be insulate(

by means of mica, in which case it is possible to provide a means for clamping them firmly together. The sectional view taken through the inductors shows the work in the heating position. Only the edge of the bar is heated as it is progressively fed
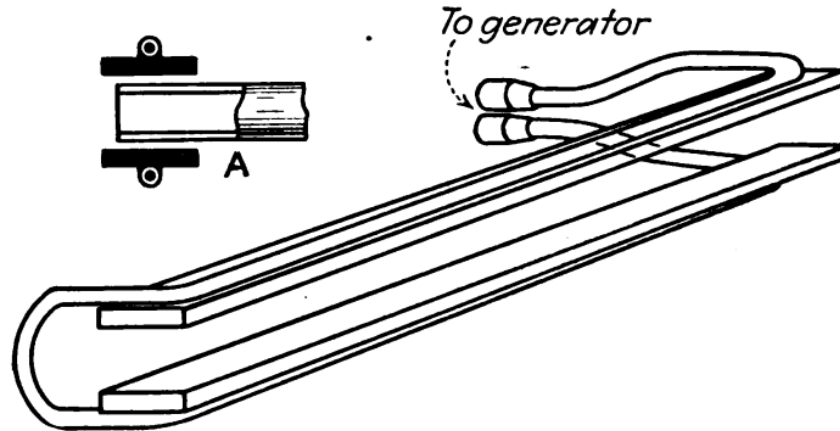

FIG. 78.—A two-bar-type inductor arranged so that the work can be rolled between the plates as may be required for annealing the ends of shells or tubes.

through the inductors. A spray-quench unit, not shown, is located at the left of the heating inductor, in order to complete the hardening cycle.

In making heating coils for continuous feed operations, it is often desirable to use copper tubing made into the form of a
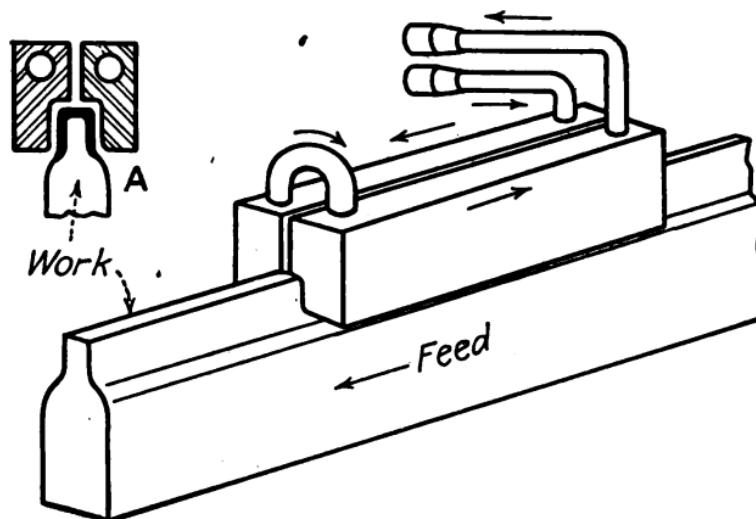
FIG. 79.—A solid-type parallel inductor used for the transfer of heat to the edge of a long shear blade, requiring progressive hardening.

hairpin, under which the parts to be heated are fed. With such a coil it is often necessary to bend the end of the coil upward, as illustrated in Fig. 80. If the coil remains on a true horizontal plane, as shown at A, there may be a likelihood of excess heating

on the edge of the work, as at *B*, especially if sharp corners are encountered.   Usually the thinner the work, the more necessary it is to provide this bend at the end of the coil.
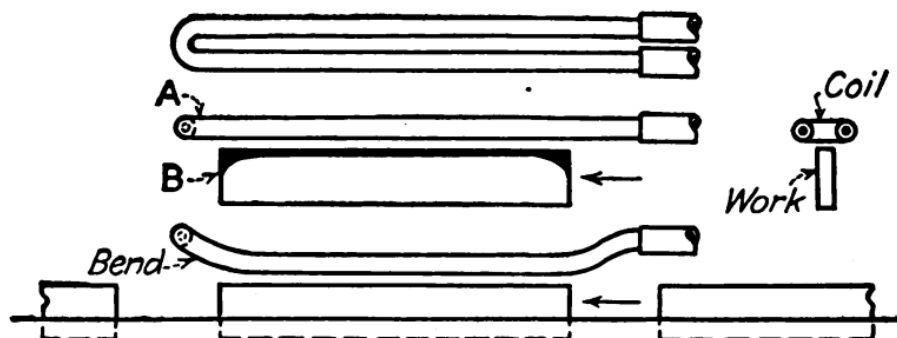

Fig. 80.—When using hairpin-type coils for heating the edge of narrow strips, it is advisable to turn the end of the coil upward to avoid overheating on the corners of the work.

Miscellaneous Coils.   In Fig. 81 is illustrated a flat-type coil, which has broad uses in the heating of parts requiring uniform heat.   This coil is made from a flat piece of copper.   First, four holes are drilled through the entire length, then the slots are cut as shown, so that the current will circulate back and forth, entering through the connection at *A* and leaving at the connection B.   At the end of the coil, where provision is made for circulation of the cooling water, the small plates *P* can be attached, as indicated.   Coils of this type can be made in various sizes and styles, and are particularly suitable in cases where a single hairpin coil is applicable.
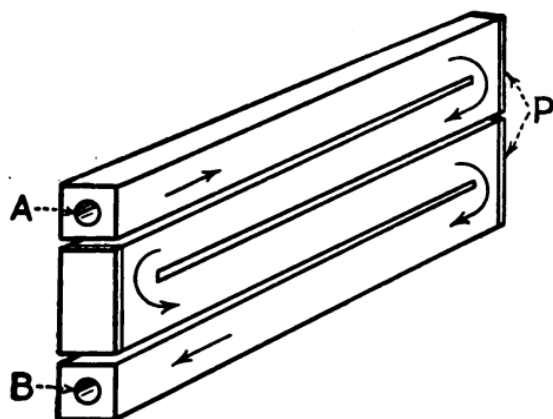

Fig. 81.—A flat-type coil made from a block of copper, with drilled holes for passage of water and slots cut between sections to distribute the passage of high-frequency current.

The coil shown in Fig. 82 is used for the heating of the end of a drawn cup which requires forging.   The coil in this case is made from a strip of copper, to which a cooling tube is brazed, as may be seen.   The area of the part to be heated is approximately 2 in. in length, and the temperature required is 1800°F.   The coupling of the coil is approximately $\frac{3}{16}$ in.

In using coils of this type, a very even distribution of heat can be produced, but solid coils of the same type are limited in their

height. The proportions shown in this particular coil are very satisfactory, however, and the example is representative of the possibility of providing a high temperature heat to a localized surface. In other methods it would be necessary to heat the entire part, which often is objectionable. With high-frequency heating the temperature change is so localized and so quickly applied that the part can be removed by hand and inserted into the forging press without insulating precautions that normally would be required.

A single-turn coil used of soldering a socket to a reflector is illustrated in Fig. 83. The socket is assembled to the reflector body and a ring of solder is placed in the joint. Because of the thickness of the joint of the parts to be heated, the heat is quickly applied and as a rule the coupling of the coil can be made

FIG. 82.—A large single-turn coil used for heating the end of a drawn steel shell, for a forging operation.
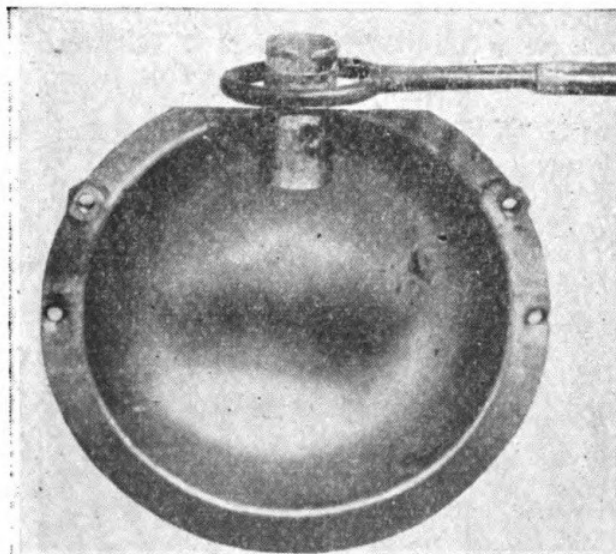

FIG. 83.—A small single-turn coil used for the soldering of a socket to a reflector.

somewhat greater than for the average heating operation, particularly where a greater mass of metal is to be considered. The spacing of the joint where the coil meets should be held to a minimum,

so that an even distribution of flux density will prevail.   Soldering operations of this kind can be effectively handled in multiple, using a series-type coil.

In Fig. 84 is shown a double hairpin-type coil used for joining a steel ring.   This coil practically surrounds the surface to which heat is to be applied, as will be seen.   A coil of this type can be made to heat a wide variety of surfaces and because of its simplicity in design can be quickly formed.
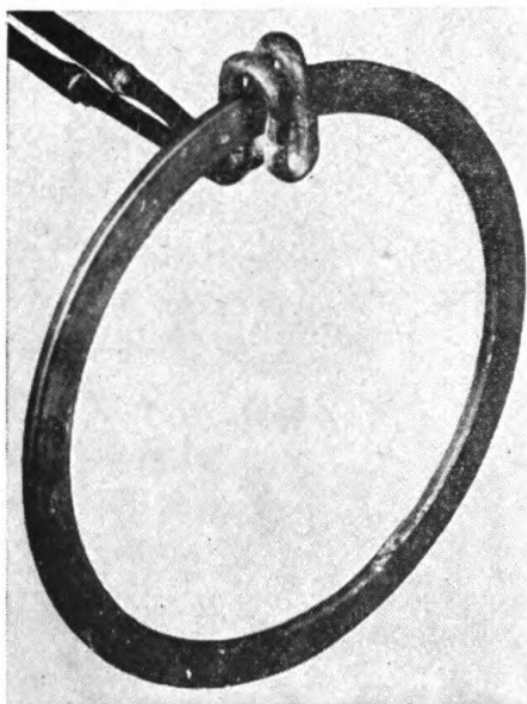
Sometimes it is necessary to apply heat to the corners of an assembly such as shown at A in Fig. 85.   In this case an analysis has to be made of the magnetic-flux dissipation from the coil to insure uniform heating.   The use of a hairpin coil, as shown at B, would result in the absorption of some of the energy on the end-plate C rather than in the corner.   This would indicate that the coil should be provided with a formed end as shown at D, in order to provide for an extra amount of flux to this corner area.

FIG. 84.—A double hairpin-type coil used for the joining of a steel ring.

On other parts presenting a similar condition, it would be possible to use a coil formed on the end, as shown at E.   Still another way to insure maximum flux density in corners is to make a heating inductor as illustrated at F.   In this design, the ends of the connecting tubing are fastened to a small copper block. This block is provided with a saw cut at G, so that the high-frequency current will pass down to the corners.   The end of the block is milled out for the circulation of cooling water, as shown at H.   A cover plate is then attached to the face of the block to complete its structure.

In Fig. 86 is represented a piece of work requiring the heating of three inserts for brazing purposes, for which a specially formed coil should be provided.   Assuming, however, that a symmetrical coil were used, as shown at the upper portion of the illustration,
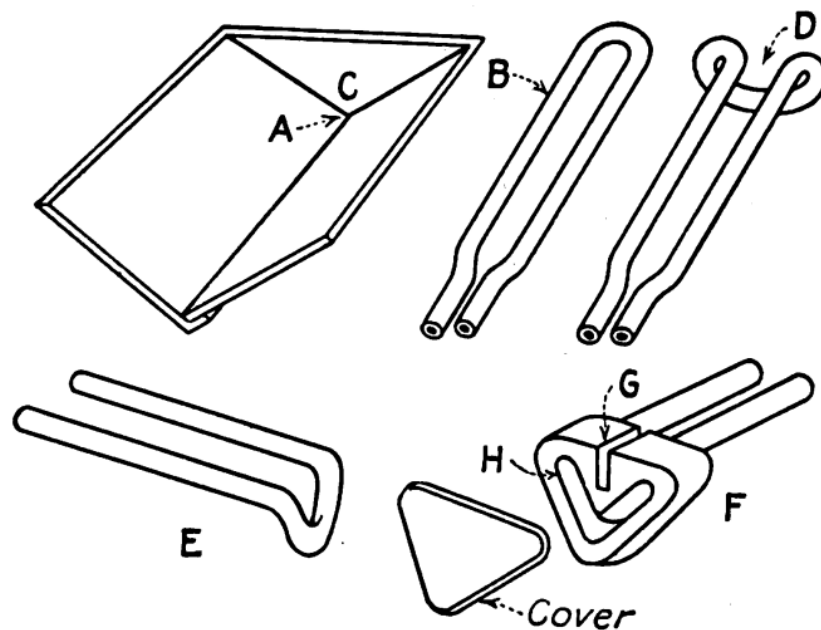
Fig. 85.—When heat has to be thrown into a corner, it is usually necessary to provide a coil which will transfer an extra amount of heat to this joint.
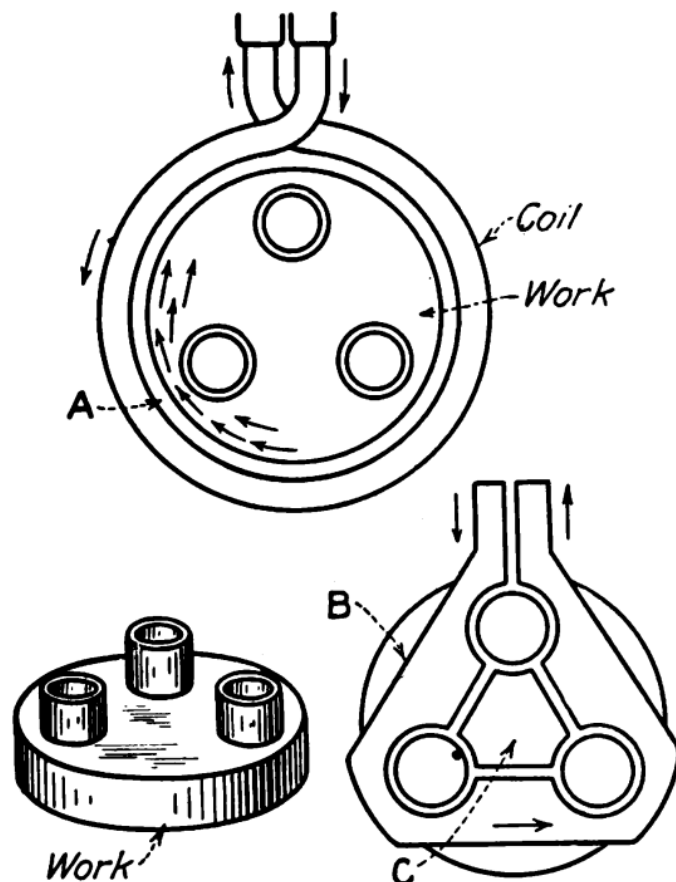
Fig. 86.—Principles involved in brazing three lugs to a cap by means of a single-turn coil, showing the correct and incorrect methods.

there would be a tendency for the circulating current to crowd through the narrow portion of the work, as shown at *A*, and excessive heating would take place. Also, there would be insufficient heat at the inside portion of the insert.

To handle such an operation a series-type heating coil, as shown at *B*, would be required. In that case the high-frequency current would enter at one con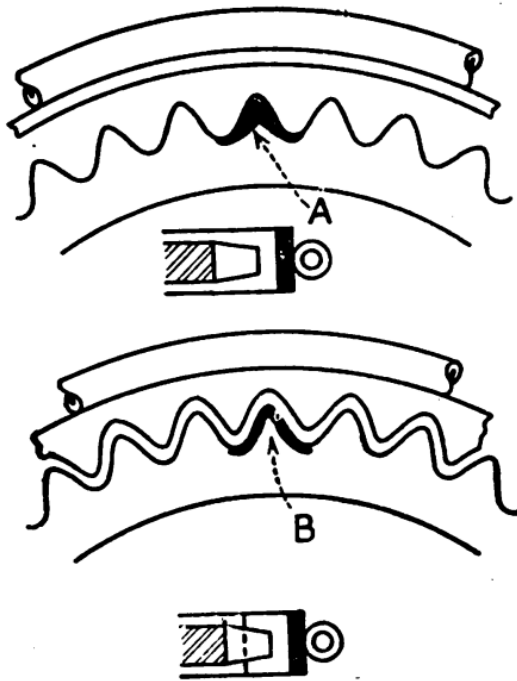nection, then completely surround the three inserts, and pass out through the other connection. It would be necessary, however, to use a coil insert, as shown at *C*, which would act as a flux concentrator. In making such a coil it would be necessary to provide cooling not only for the outer section, but also for the insert.

FIG. 87.—When heating irregular surfaces such as sprocket teeth, it is essential to use a formed coil, usually of the cast type, in order to assure uniform heating.

When hardening the outer surface of a part having a variation in depth, such as the sprocket shown in Fig. 87, there would be a tendency for the outer portion· of the teeth to absorb more heat than at the root. Assuming that a single-turn flat-type induction coil were used, we would get a heat pattern such as that shown at *A*, on which the points might become overheated. To overcome this condition, the coil should be made to conform to the approximate outline of the teeth, like that shown in the lower portion of the illustration. A coil of this type can be cast to size and with a carefully made pattern should require very little cleaning to assure uniform heat. With a formed coil of this type, the heated zone will be produced as shown at *B*, with a more uniform density of heat around the entire profile of the tooth, especially at the root.

Sometimes it is necessary to provide a tubular-type coil for maximum heat concentration to the surface of a part, where a solid-type inductor might be preferred to a multiturn coil. Th

design of a coil for such an operation is illustrated in Fig. 88. A copper tube of the size required is cut off as shown at *A*, then a section of small tubing is wound around the outside, as illustrated at *B*. Finally the coil is saw-cut with a spiral, as shown at *C*.

An induction-coil assembly for the heating of continuous strip is illustrated in Fig. 89. This coil is longer in relation to its diameter than would normally be necessary for hardening operations, but in cases where continuous heating of material is desired, a coil of this type works satisfactorily. In this application, the heating-coil unit is placed adjacent to a power press. The material being heated is a magnet-steel strip which is heated to 1800°F., then blanked, formed, and hardened in one operation. The temperature attained in the steel as it enters the press is slightly higher than that required for hardening, but during the blanking and forming operation the temperature drops to approximately 1525°F., then is quenched in oil. The steel is ⅛ by ⅝ in. in size and is heated by a 30-kva. input high-frequency unit. As a

FIG. 88.—Constructional details of a spiral-type coil made of a copper sleeve to which copper tubing is attached for cooling purposes.

result of high-frequency heating, the steel receives a higher indexing magnetism and a better magnet is produced. Another direct saving is a marked reduction, or practical elimination, of rejects.

Flexible leads can be used with induction heating setups, although their application should be limited to heating requirements which might make them necessary. These leads can be made from sections of high-pressure metallic tubing of the flexible type, as illustrated at *A* in Fig. 90. It is essential, however, that the braided cover, as well as the inner bellows, be made of a pure copper, having high electrical-conductivity qualities. For safety it is well to provide a rubber hose on the outside, as
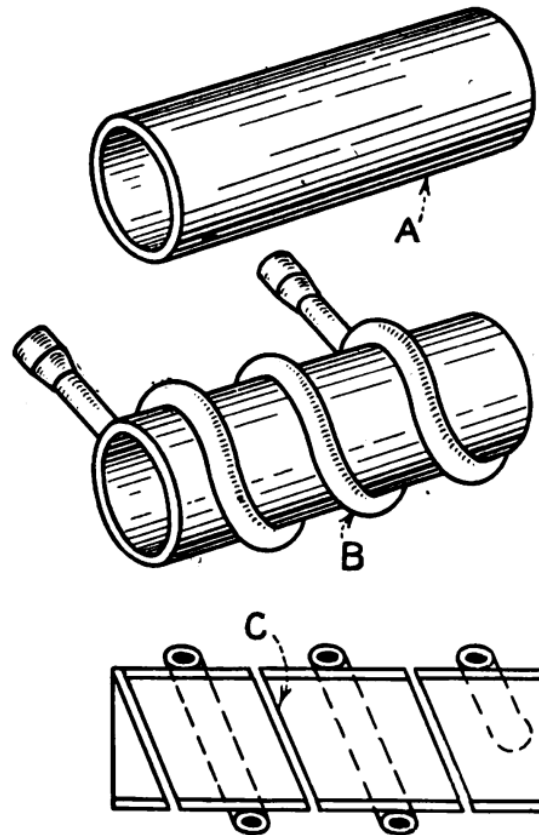
indicated. Leads of this kind provide for the passage of high-frequency current from the generator to the work coil, as well as for the passage of cooling water.
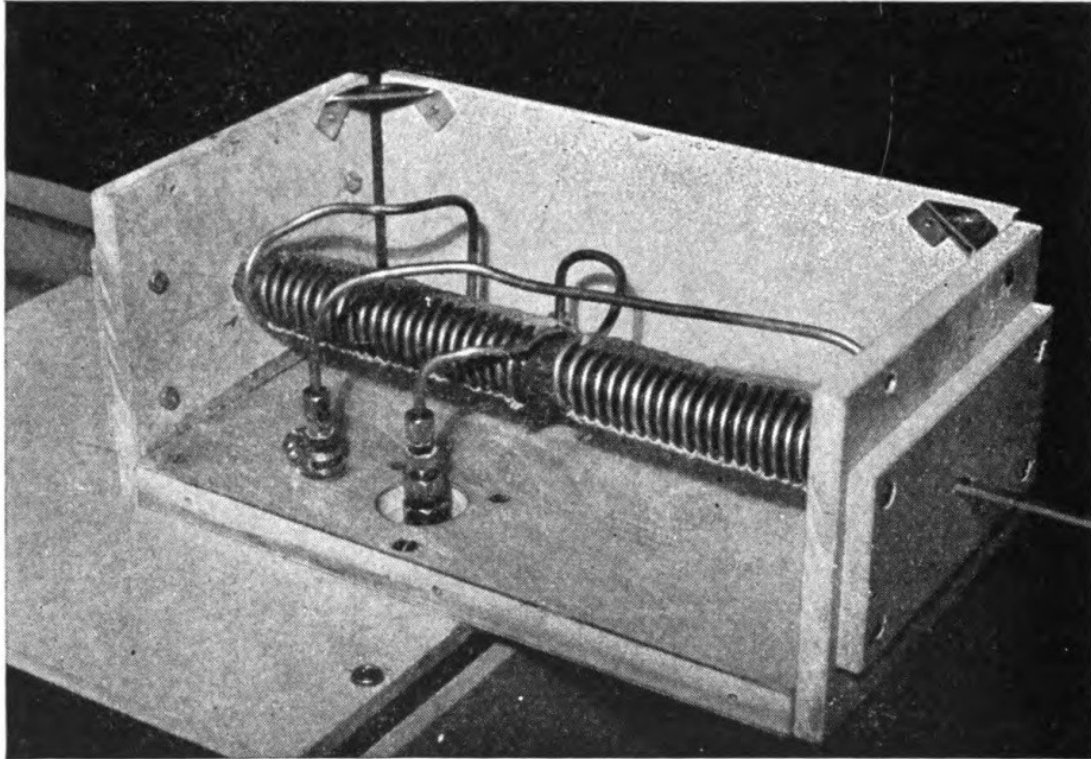

Fig. 89.—A long heating coil, which is used for the continuous heating of steel strip. (*Courtesy of Ecco High Frequency Corp.*)
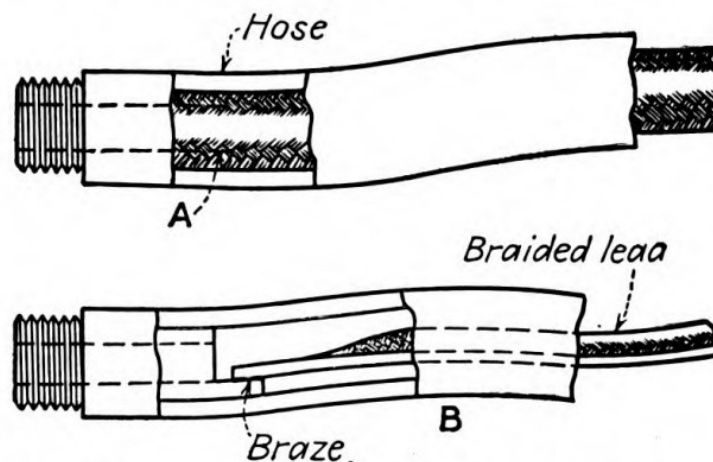

Fig. 90.—Two types of flexible leads which can be used in connection with induction-heating generators.

Another way to make a flexible lead is illustrated at *B*. Here the braided-copper lead is brazed to the connector and then covered by a rubber hose as shown. With this type of lead, it is necessary to have a similar connection at the other end for attaching the work coil.

In Fig. 91 is illustrated a multiturn coil provided with insulation in the form of woven glass sleeving. About the only advantage of insulation of this type is the elimination of metal-to-metal contact of the coil windings, which in this case are very close together. Where intense heat is to be applied, however, insulating material of this kind does not give long service and other means of insulation are more practical. A copper-tube coil can be lacquered, or coated with insulating varnish, then baked, if its use is not in connection with flux as used for brazing. Plating is not usually recommended, since high-frequency current travels on the surface of a coil, and plating
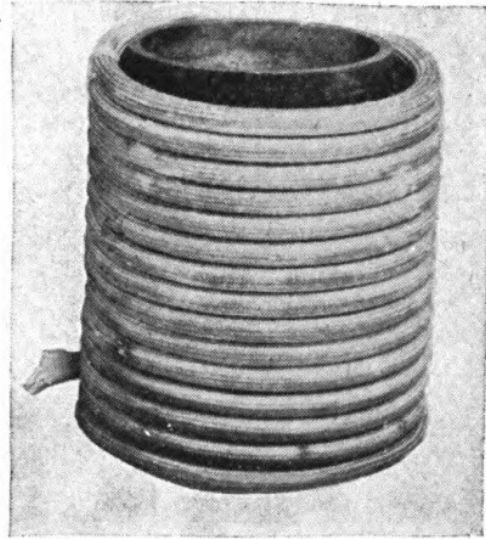

FIG. 91.—A multiturn heating coil covered with woven-glass sleeving. Coil insulation can also be obtained by applying a baked coat of insulating varnish.

materials, such as chrome, are not good conductors. Ceramic cement provides good insulation around a coil and may be used where protection is desired.
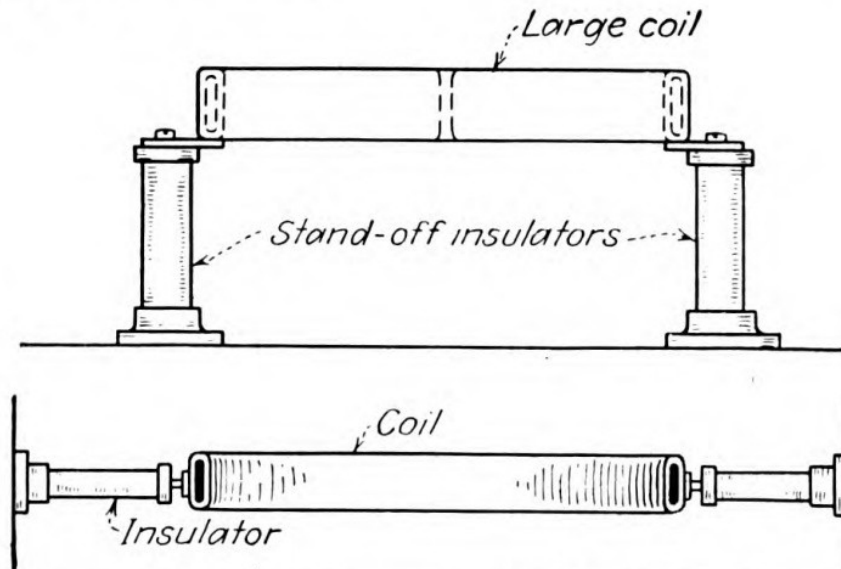

FIG. 92.—Large heating coils can be supported by stand-off insulators, in order to assure rigid mounting.

Heating coils sometimes require outboard-supports, because of their sizes and shapes. While such supports can be provided in various ways, it usually is best to consider an insulator that will prevent the loss of high-frequency current from the coil. A

satisfactory type of support is a stand-off insulator, as illustrated in Fig. 92.   Small extensions can be brazed to the bottom of the coil, then the insulator can be attached to the extensions, so that a rigid coil mounting is provided.   It also is possible to support induction-heating coils from their sides, as shown in the lower portion of the illustration.   In this case, the end of the stand-off insulator is brazed to the side of the coil, then the base of the insulator is mounted to some convenient vertical support at the sides.

Many other forms of brackets and supports can be used for coils and, in cases where insulating material such as asbestos board is used for the top of a work table, there is no objection to providing copper feet or legs in the coils for alignment purposes. Other means of supporting coils may be seen in various illustrations showing hardening and brazing installations.

CHAPTER IV

BRAZING, SOLDERING, AND JOINING

The application of high-frequency induction heat for the joining of metal parts with solders and brazing alloys offers a wide variety of applications. In many ways this process of joining metal parts enables the adoption of new manufacturing techniques, such as the design of fabricated parts to supersede those made from one piece, especially where silver brazing alloys are used as the bonding medium. The outstanding features of induction joining are the speed with which heat can be applied; the uniformity of heat transfer, once a cycle has been established; and economical heating cost when only a local surface is treated in contrast to an entire component or assembly.

Low-temperature solders, melting at temperatures of 250 to 500°F., for the joining of metal parts can be bonded at exceptional speeds, because of the capacity of high-frequency current to cause metals to reach this relatively low temperature so quickly. With little difference in time, however, the harder solders, having a melting range of 500 to 700°F., also are quickly melted into joints more effectively than by any other means. Soldering operations that ordinarily might require a half minute by irons or gas flames can be performed by induction-heating equipment in a second or two.

High-frequency induction brazing with silver alloys provides an excellent means of joining together ferrous, nonferrous, and dissimilar metals. An outstanding advantage of this is that the fluidity of silver alloys provides penetration into restricted openings, which other alloys might not reach. Capillary attraction results in their spreading evenly over the surfaces to be joined, thus forming a solid bond.

To some extent silver brazing is a form of hard soldering. However, the joint usually becomes stronger than the alloying material thus making exceedingly strong bonds possible. In many cases silver brazing, using high-frequency induction heat for the melting of the alloy and the heating of the parts to be

joined, will produce joints with strengths equal to those obtained by copper brazing, and when considered as a substitute for copper brazing, the need of a controlled-atmosphere furnace can be eliminated.

Silver alloys melt at temperatures ranging from 1100 to 1500°F., according to their composition. They have tensile strengths of 40,000 to 70,000 lb. per sq. in., but with some designs can provide joints with strengths in excess of 100,000 lb. per sq. in. To obtain the maximum strength, the spacing between the parts to be joined must be closely held. The better the fit, the stronger the joint.

In the long run induction brazing with silver alloys is more economical than other methods. It is quick, produces a uniform flow of the alloy, uses a relatively small amount of it, and produces a joint that requires practically no finishing. Briefly, a silver-brazed joint combines strength, smoothness, and ductility; it assures leakproof assemblies, and withstands temperatures that ordinarily would melt solder. High-frequency induction heat for silver-brazed joints is suitable for more uses than other means of heating. The acetylene torch, for example, gives excessive heat which might have a tendency to distort parts adjacent to the brazed surfaces. The virtue of high-frequency induction heat lies in the closer control of heat to restricted surfaces which it provides.

Miscellaneous Brazed Joints. In Fig. 93 are represented various types of silver-brazed joints which are adaptable to the inductive-heating process. In the example at *A*, a preformed silver-alloy ring is brazed at the joint as indicated and when heat is applied around the bottom surface of the shaft the alloy flows in such a way that it fills the surface between the two parts.

At *B* is shown a joint in which the brazing material is placed at the edge of the flange, so that when it melts it runs down through the joined area. In the example at *C* the silver-alloy washer, as indicated at *D*, is placed between the shoulder of the shaft and the edge of the flange. With this type of brazing application, it is necessary to apply pressure on the shafts so that when the silver ring melts the excess material will go down into the joint. At *E* is a similar application, although in this case the insert is made in the form of a bushing, which likewise requires a pressure applied to it, so that when the silver ring

melts the flow of the material will go into the joint, and thus provide a metal-to-metal contact.

In applying bushings of this type, it also is possible to use a preformed ring of silver material placed under the shoulder, as shown at *F*. In the example at *G*, a ring is placed under the head of the bushing which, when melted, will flow into the joint. If an insert of this type has sufficient weight, it is likely that the part will settle into position as soon as the alloy is heated to its flowing point, and thus form a metal-to-metal contact. However, with light pieces it is preferable to apply a suitable pressure to insure a tight metal-to-metal joint.
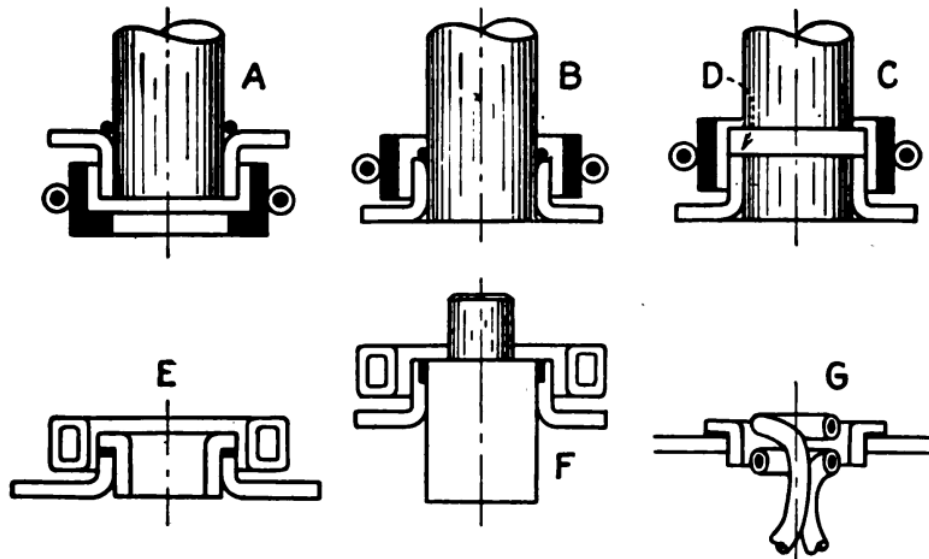
FIG. 93.—A variety of brazed joints that lend themselves favorably to induction heating.

Another group of brazed joints is illustrated in Fig. 94. The example at *A* represents a shouldered flange brazed to an upset sheet-metal opening. For this application, a washer of silver alloy is inserted prior to the assembly of the two parts. At *B* is illustrated a method for mounting a tube to a flange, in which the silver-alloy disk is placed under the edge of the tube and then squeezed down into position after it has melted. The alloy then runs up through the joint and forms a solid bond.

Another way to assemble a tube to a flange is shown at *C*. Here the performed silver-alloy ring is placed at the upper portion of the joint. When heat is applied the alloy will flow down the sides of the tubing to the bottom edge, thus covering the entire surface. Another way to perform this operation is to provide a counterbore at the upper portion of the flange and set the silver

ring into it, as shown at *D*. One of the most satisfactory methods, however, is to machine a groove either into the flange, or the member to be inserted into it, and to place a preformed ring of silver alloy into the groove prior to the assembly of the two parts. The example shown at *E* has a groove cut into the flange and, when the alloy reaches melting temperature, it will tend to flow up and down, so that the entire joining surfaces are covered. Still another way to braze such a joint is indicated at *F*, in which a preformed ring of silver alloy is placed within the tube. When the alloy melts it will run out along the edge of the tube and up the sides of the joint.
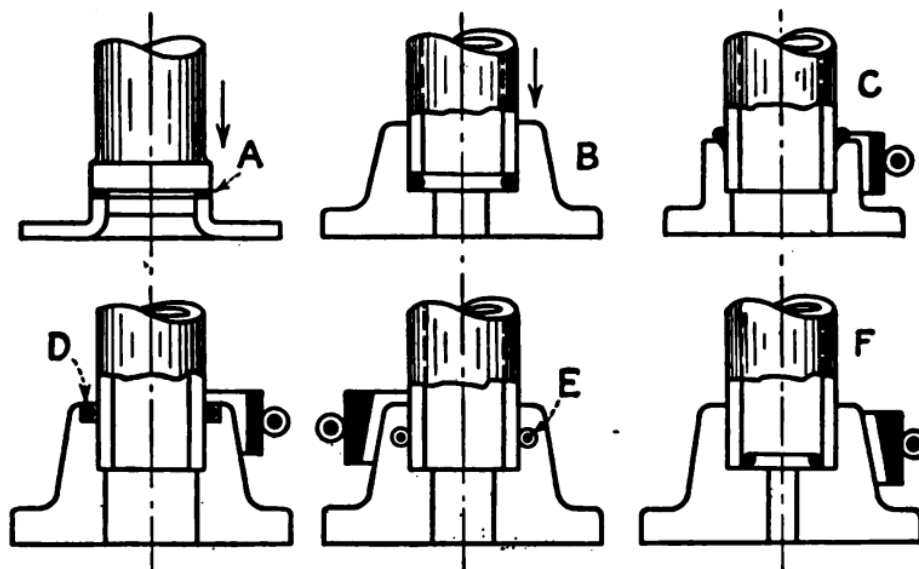
FIG. 94.—A miscellany of induction-brazed joints showing various methods for applying silver alloy.

In joining together sheet-metal assemblies, such as tubing and covers, or drawn shells and caps, often required for containers and the like, there are many varieties of brazed joints well adapted to the application of induction heat. In Fig. 95 are shown a variety of these joints. In the example at *A* both edges of the assembly are formed out, so that a preformed silver-alloy ring can be inserted between them, at assembly, as shown. For the joint at *B*, however, the silver-alloy ring is placed underneath the cover and, when heat is applied, the alloy will flow up through the joint. One of the better types of joint, however, is illustrated at *C*. Here the inner body is preformed with a groove, into which a silver-alloy ring is placed before assembly of the cap. After heat has been applied to melt the alloy, it will

flow upward toward the top of the joint and also downward, so that both contacting surfaces become completely covered, thus forming an effective bond. For the joint at *D*, the pre-
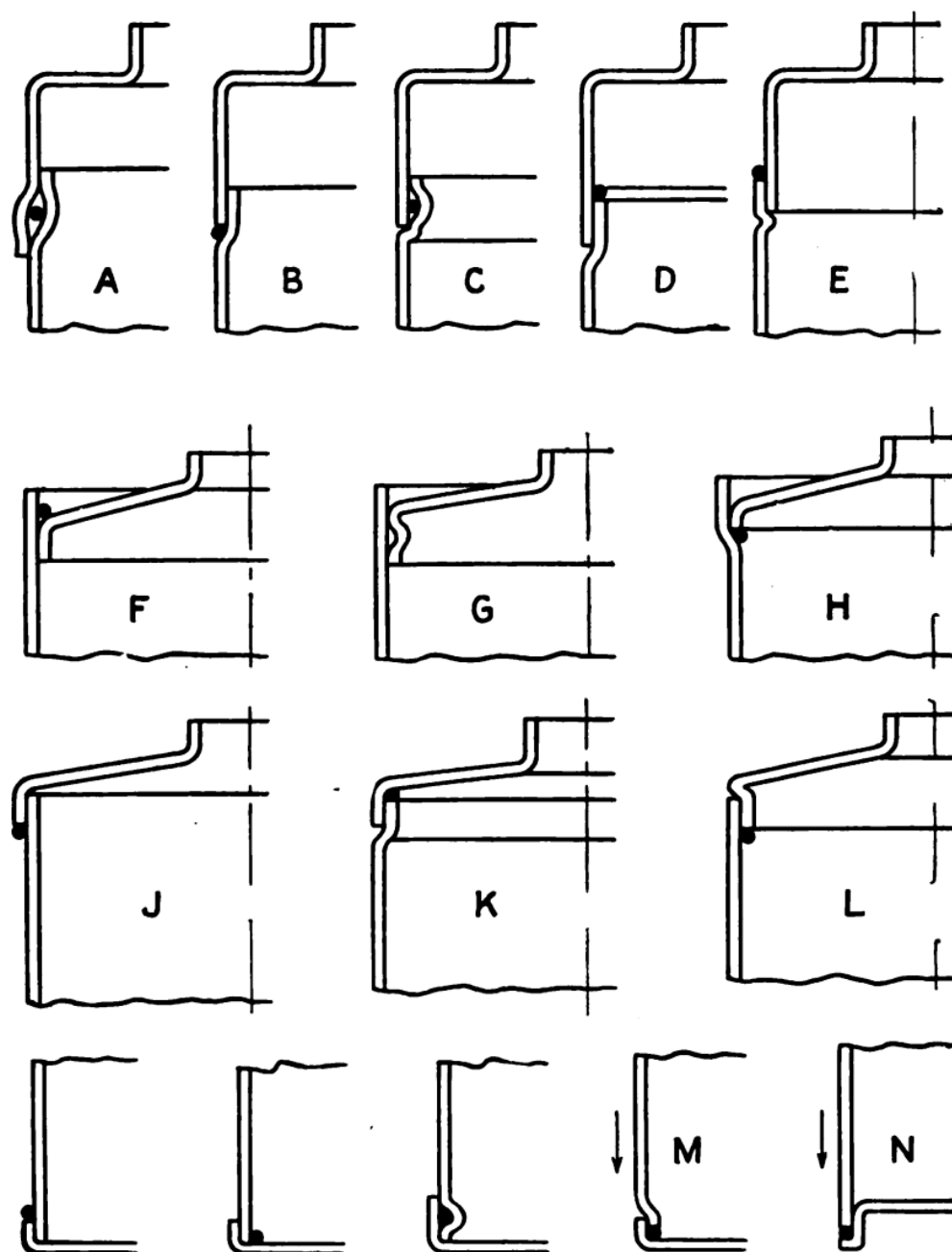

FIG. 95.—Various ways in which silver alloy can be used in connection with the induction brazing of sheet-metal parts.

formed wire alloy is placed on the inside surface and, when it melts, flows downward through the joint.

The reverse of this is shown at *E*, where the alloy ring is placed on the outside edge and, when melted, flows through the inside joint. In the example at *F* the cover is inserted on the inside of the sleeve and a preformed ring of alloy is placed on

the inside which, likewise, flows through the joint.   The example at G also is arranged so that the cover has a groove rolled into it.   Into this the alloy ring is placed prior to assembly, so that upon being heated the metal will flow up and down.   Another form of braze, in a similar assembly, can be seen at H, where the ring is placed on the inside and, when melted, will flow upward. The example at J is similar, though here the cover is placed over the outside of the body.
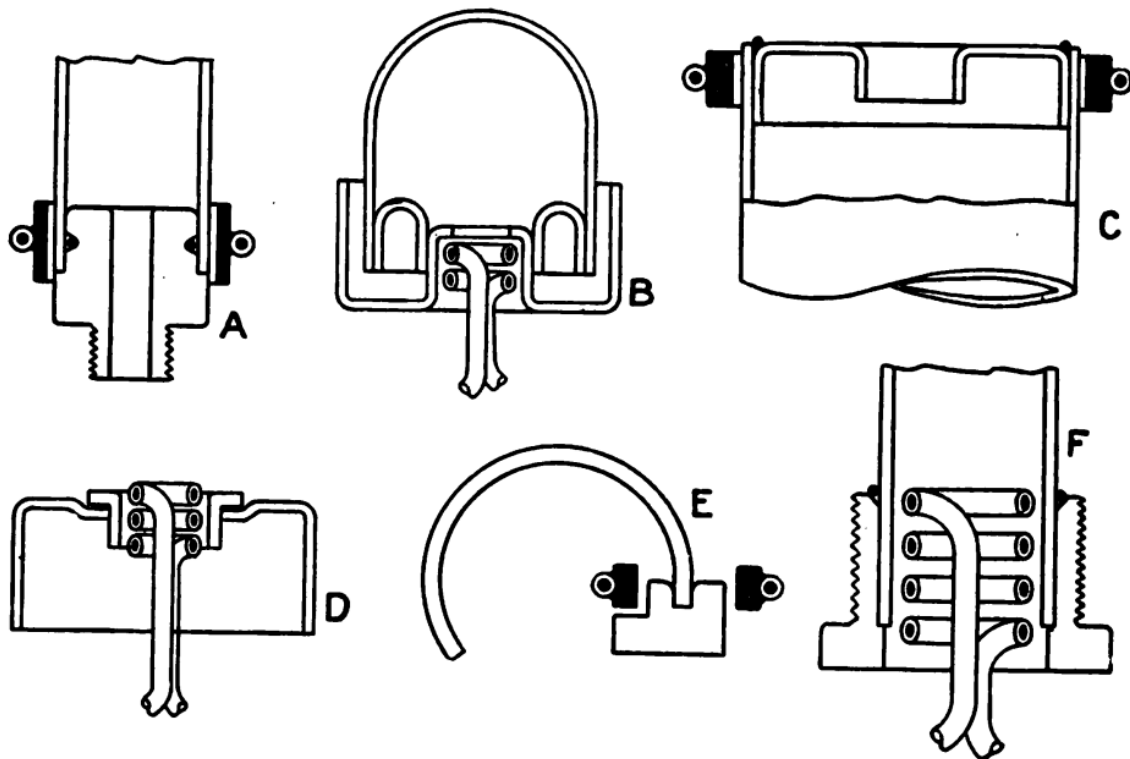
FIG. 96.—Six representative types of joining operations performed by means of high-frequency induction heat.

Another type of assembly, comprising a cap to a sleeve, is shown at K, in which the preformed alloy ring is placed inside, as shown.   As soon as the surrounding metal is heated sufficiently to flow the alloy, it will run down through the joint.   In the example at L, however, the ring is placed on the inside and must flow up into the joint.   With this type of brazing it is important that the ring remain in position, and usually it would be better to turn the part upside down, to ensure a perfect bond, although because of the characteristics of silver alloys they will flow upward practically as well as downward.

The five examples shown at the lower portion of the illustration are representative of the method used for applying shallow covers to tubular bodies.   The preformed rings are mounted in various

ways somewhat along the lines already discussed. With the joints at *M* and *N*, however, it is necessary to apply pressure to the outer sleeve in order to form a metal-to-metal contact, as soon as the preformed silver-alloy ring begins to flow.

Production-brazing Setups. In Fig. 96 are illustrated a variety of brazing operations for miscellaneous types of metal parts, which are representative of some of the joints that can be made by high-frequency induction-heating generators. The assembly at *A* includes a tube to which a solid-type insert is brazed. The silver-brazing ring is placed within a groove, cut
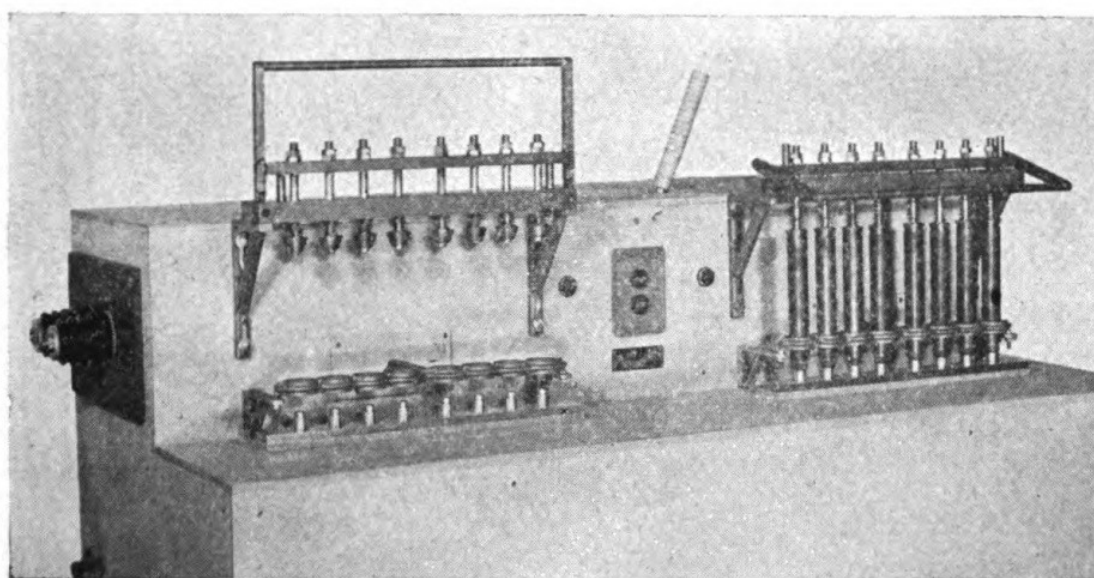
FIG. 97.—A typical two-station brazing table arranged with two sets of coils and fixtures, assuring maximum output from a single generator. (*Courtesy of Induction Heating Corp.*)

into the plug, prior to assembly, as shown. The tube is then placed over the plug, and induction heat is generated to the surface by the single-turn inductor, as shown. The table used for brazing is illustrated in Fig. 97. In this case two stations are used, and the one at the right shows the arrangement of the fixture during the brazing operation. The fixture at the left, however, is open and ready for loading. There are eight pieces brazed simultaneously, and each assembly is held in place firmly by means of individual spring plungers, located on the upper cross plate of the fixture. After the proper heat has been applied to the joint, the silver-brazing alloy flows both upward and downward, so that a uniform brazing action results. Pressure on the tube against the shoulder of the insert assures correct

alignment and eliminates the possibility of the tube's moving out of place while being heated.

In Fig. 98 is illustrated a brazing setup for joining a nose cup and a spacer. Here six pieces are handled simultaneously. For this an internal-type coil is used, details of which may be seen in Fig. 96, at *B*. The silver-alloy ring is placed underneath the cup section, as shown, and when heat is applied to the inside surface of the spacer, the molten alloy is drawn up through the joint, completely surfacing the contacting areas of both parts.
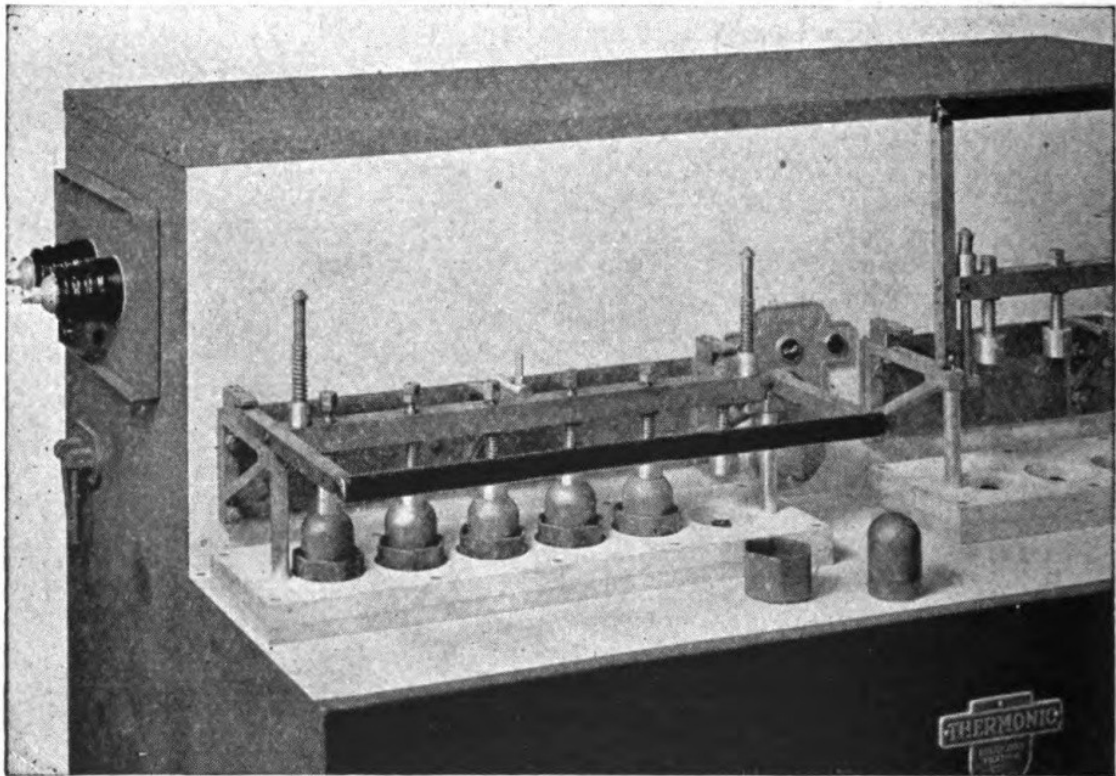
FIG. 98.—A series-type heating coil and fixture used for brazing sheet-metal assemblies. (*Courtesy of Induction Heating Corp.*)

The operation illustrated at *C* in Fig. 96 represents the brazing of a tube to a body, in which the preformed silver-brazing alloy ring is placed at the joint on top, as shown. The operation is performed as illustrated in Fig. 99. This table is arranged with two fixtures and, as will be seen, four pieces are brazed at one time. The coil is arranged so that heat is generated from the outside surface. When both parts attain a temperature slightly above the melting point of the alloy, the silver runs down through the joint, thus completing the braze.

The setup illustrated in Fig. 100 is for brazing an insert to a drawn cup, in which an internal-type coil is used. Details of

this assembly are illustrated at *D* in Fig. 96. Each insert is held firmly in place during the brazing operation, so that after the ring of alloy has melted, the excess material will be squeezed out and distributed uniformly, thus assuring a perfect metal-to-metal joint.

In Fig. 101 is illustrated a setup for soldering eight Bourdon tubes, used in the manufacture of pressure gauges, to the body
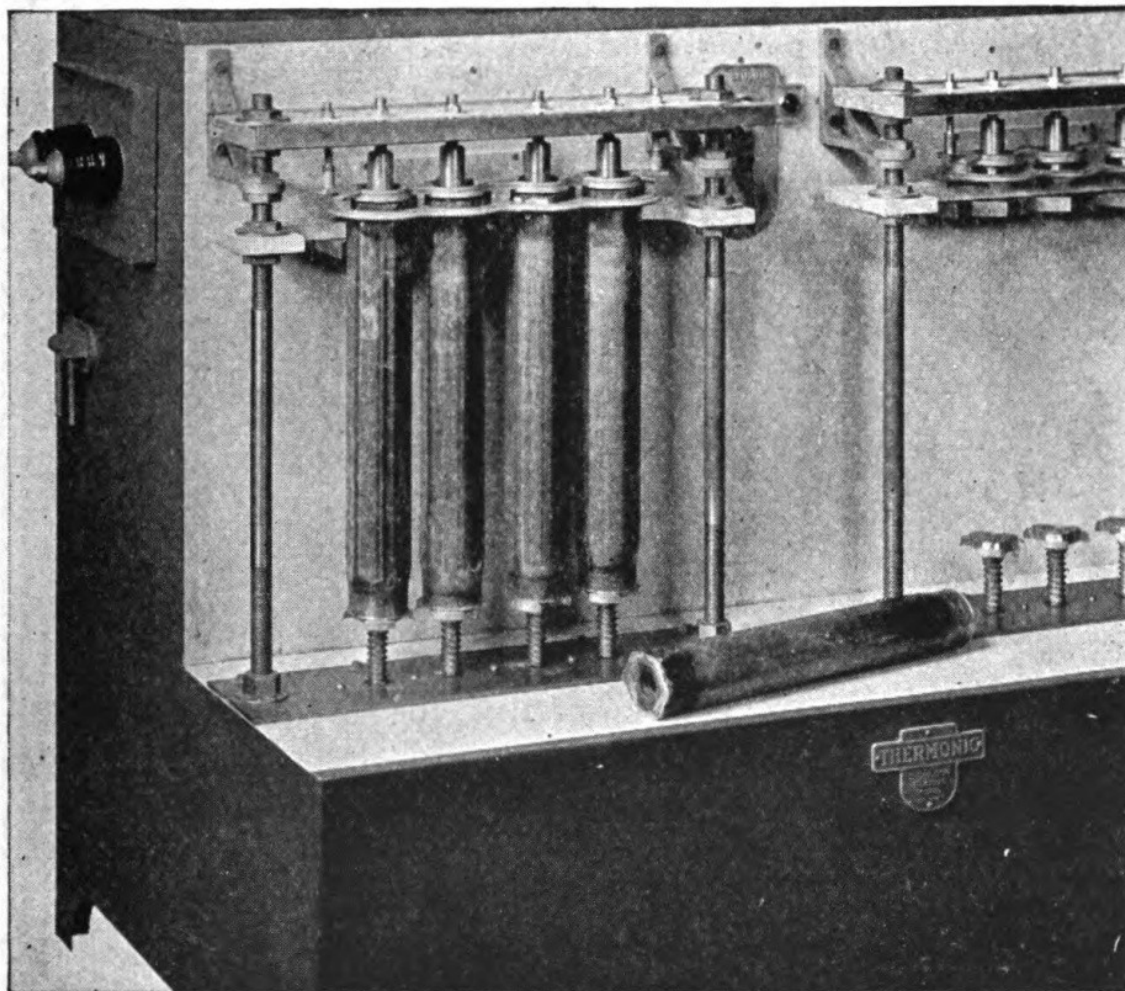

FIG. 99.—The brazing of end pieces into four steel bodies is performed simultaneously by means of a series-type heating coil. (*Courtesy of Induction Heating Corp.*)

component. For this operation two parallel-type inductors are used, arranged so that the current comes in on one bar and goes out on the other. At *E* in Fig. 96 may be seen details of the operation, showing the relation of the inductor to the parts to be brazed. The inductors, when energized, generate heat to both sides of the body from where it conducts to the tube joint.

The setup shown in Fig. 102 is used for brazing tubing to a flange and in this operation the fixture is arranged to handle four
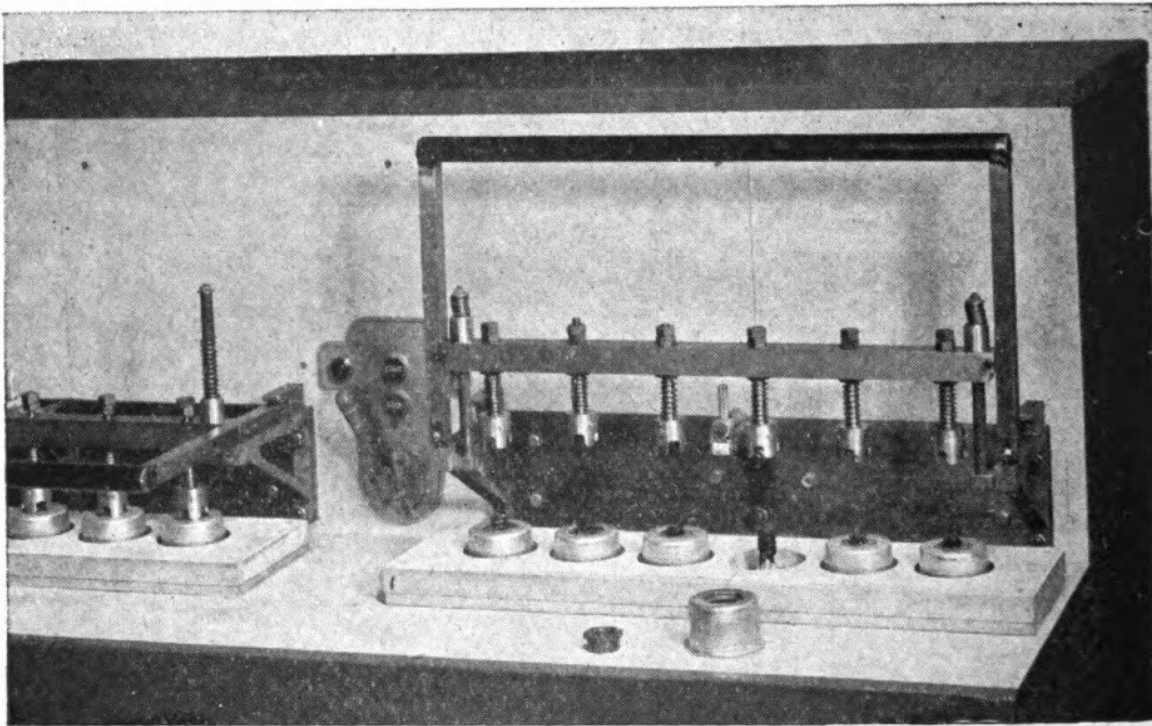
FIG. 100.—A brazing setup for joining a steel insert to a tube, in which a ring of silver alloy is used. The insert is squeezed into position when the alloy flows. (*Courtesy of Induction Heating Corp.*)
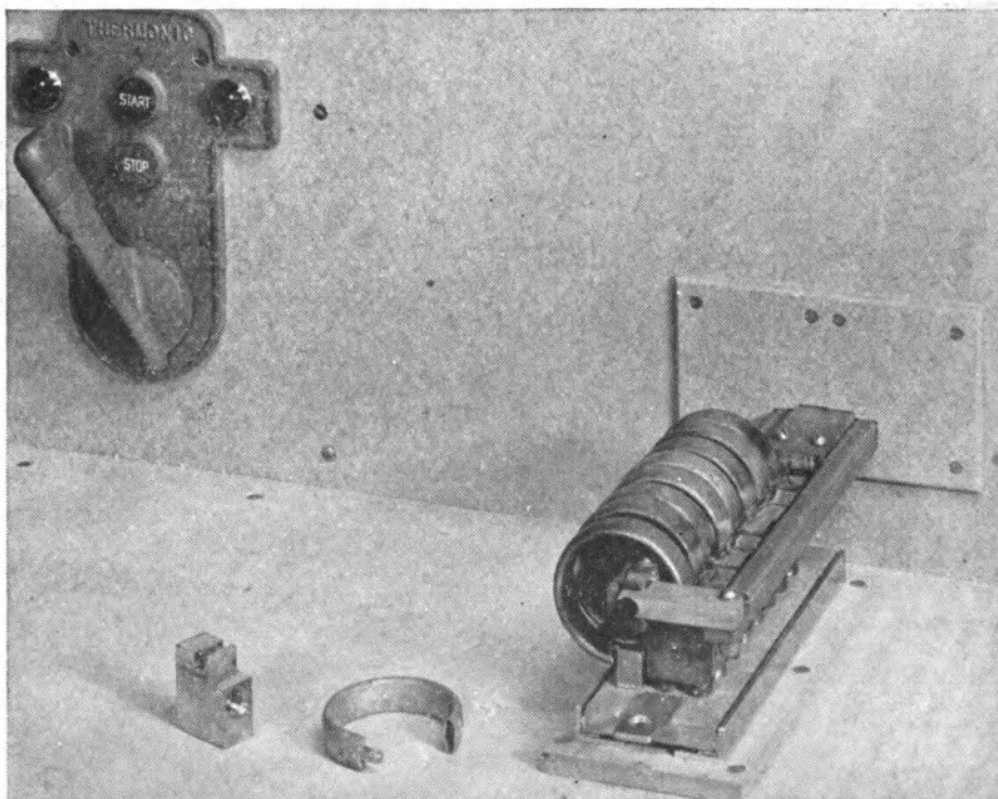

FIG. 101.—A parallel-type inductor comprising two bars connected by a bridge and used for the soldering of eight Bourdon tubes simultaneously. (*Courtesy of Induction Heating Corp.*)

pieces at one time. Internal-type coils are used, as may be seen
at *F* in Fig. 96. The silver-alloy ring is located in the chamfered
section of the flange and, upon reaching melting temperature,
flows down throughout the entire joint. The outer sleeve is
used as a guide to centralize the work over the coil.

Preparation of Surfaces. In any form of induction joining,
whether a solder or a silver alloy is used, clean surfaces are
essential. Even though a flux will have a tendency to dissolve
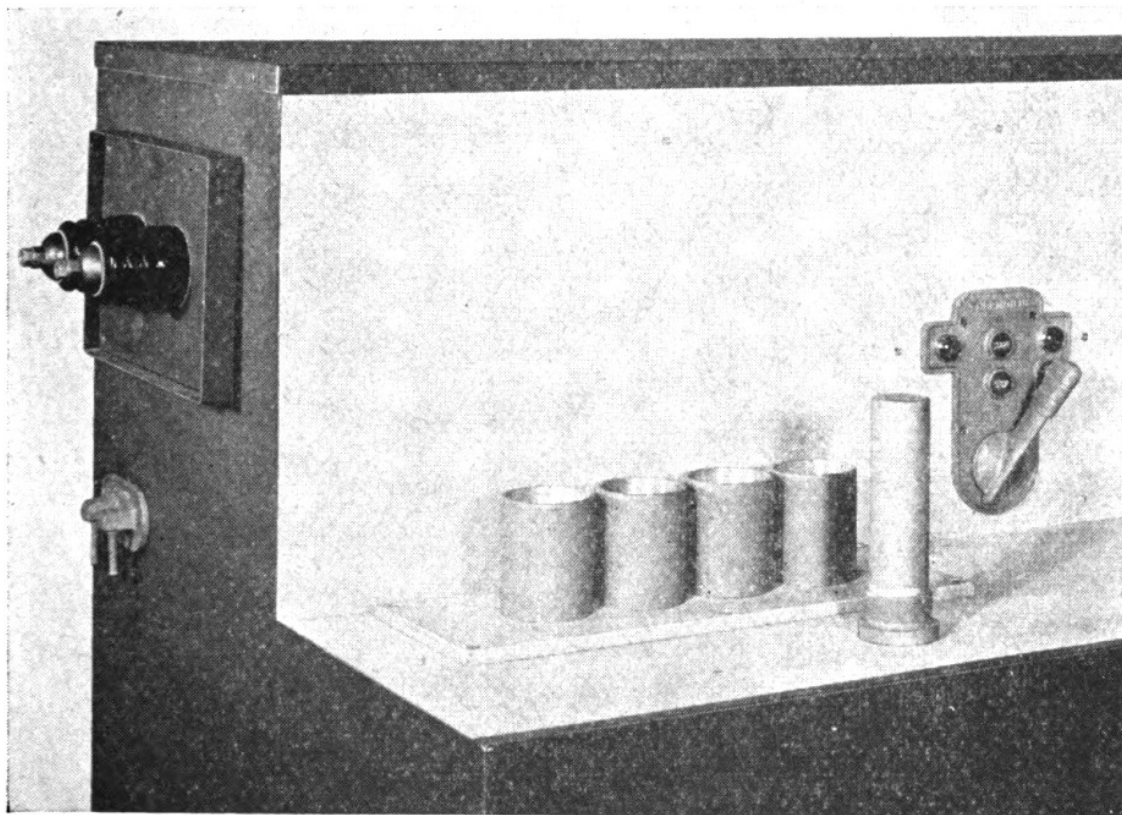
Fig. 102.—Multi-brazing operation arranged for joining a machined flange
and a tube together. Two sets of fixtures and coils are used to provide maximum
output. (*Courtesy of Induction Heating Corp.*)

oxide films on the surface of metal parts, it is better to clean the
surfaces thoroughly before applying heat. This will assure a
stronger bond. Also surfaces to be joined should be as smooth
as can be commercially produced. This procedure assures a
better flow of the alloy and a more equal distribution of it than
would result with irregular surface contact.

In connection with silver-alloy brazing, it is important that a
suitable amount of flux be applied around the areas to be joined,
as a means of protection against oxidation. This flux, when
heated, also provides a free-flowing surface for the alloy, so that
uniform bonding is made possible. Usually fluxes having a borax

base are used and are applied in liquid form, which results in a bubbling action when subjected to heat. The fluidity of the
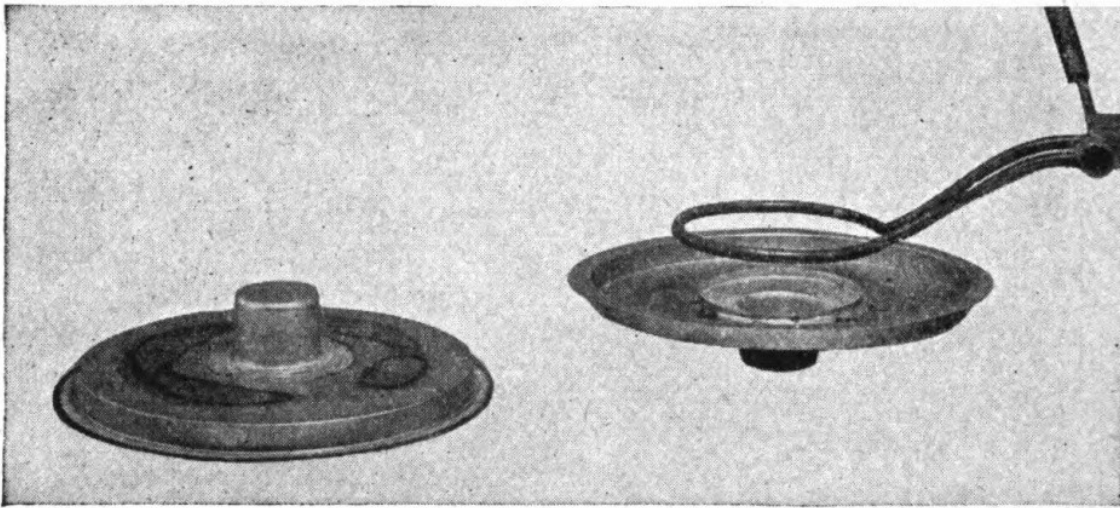

Fig. 103.—A single-turn induction coil used for the joining of two parts, where a quick heating cycle is desired.
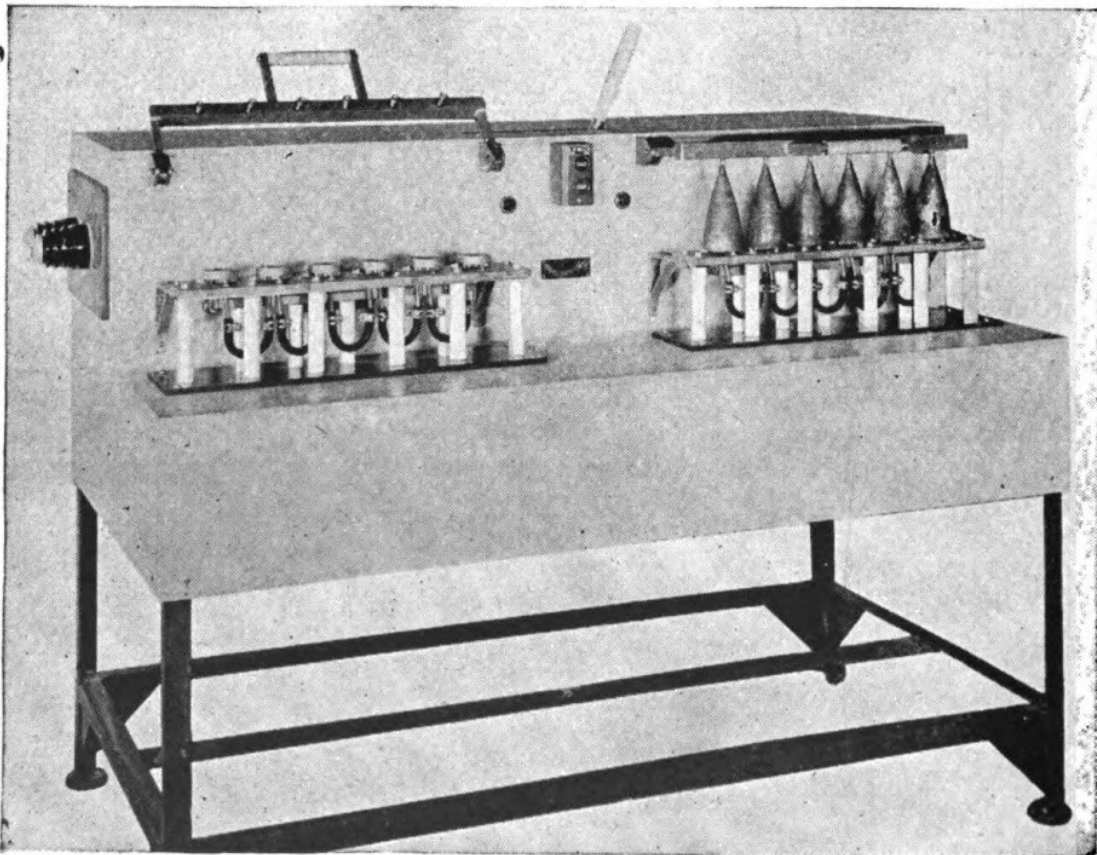

Fig. 104.—A setup for the brazing of a steel ring into a sheet-metal tube. Spring-actuated plungers assure proper contact of the pieces to be joined. (*Courtesy of Induction Heating Corp.*)

flux must be sufficient for it to flow at a temperature below that required to melt the silver alloy. With a fluidity-temperature

differential of 50 to 100°F., the flux will serve as a good temperature indicator during the brazing operation.

Induction heating can be used effectively when a small temperature differential exists between the metal parts to be joined and the solder used for bonding. This is due to the fact that the heating coil can be placed far enough away to bring the heat up gradually to the melting temperature. Then, through the automatic timer, the heat can be cut off at the exact moment when the solder flows. Such an example is shown in Fig. 103, which represents the soldering of zinc cups to turn-metal-coated flanges, where narrow temperature differentials exist.

Multiple Internal Brazing. The brazing table illustrated in Fig. 104 is used for joining a steel ring to the open end of a sheet-metal windshield. The ring is provided with a groove into which the brazing alloy is inserted prior to assembly. The parts are then assembled and placed in the fixture arranged to join six pieces at one time. The fixture is
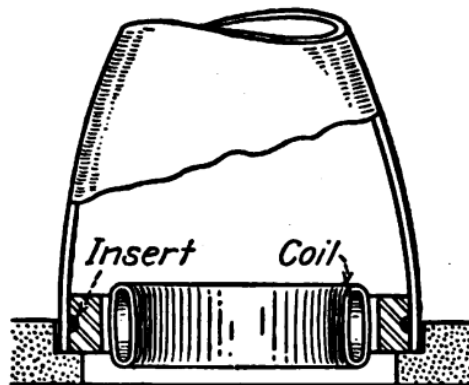

FIG. 105.—An internal heating coil of the single-turn type used for brazing a ring to the inside of a drawn cup. Heat is concentrated to the heaviest mass in order to assure a satisfactory braze.

provided with a hinged bar at the top, arranged with plunger and individual spring plungers, which hold the windshields in position.

A cross-sectional view of the parts being joined, the locating portion of the fixture, and the internal coil used for this operation are illustrated in Fig. 105. Jumper connections are used between the coils to provide for a series connection, whereas copper tubing is joined over the ends of the coil connections to provide for the continuous passage of cooling water. The coils themselves are made from a section of large copper tubing, formed into an oval shape as shown.

In Fig. 106 is shown a sheet-metal body onto which three inserts are to be soldered, as well as the two different heating coils which are used for heating. The upper coil, shown at the top, is arranged so that two inserts are soldered simultaneously. The lower coil, which also is of the single-turn type, is arranged to solder the side insert. These coils are shown in the relative positions in which they are used.

In soldering parts such as shown in this example, it is possible to attain a heat which will melt the average solder in a relatively
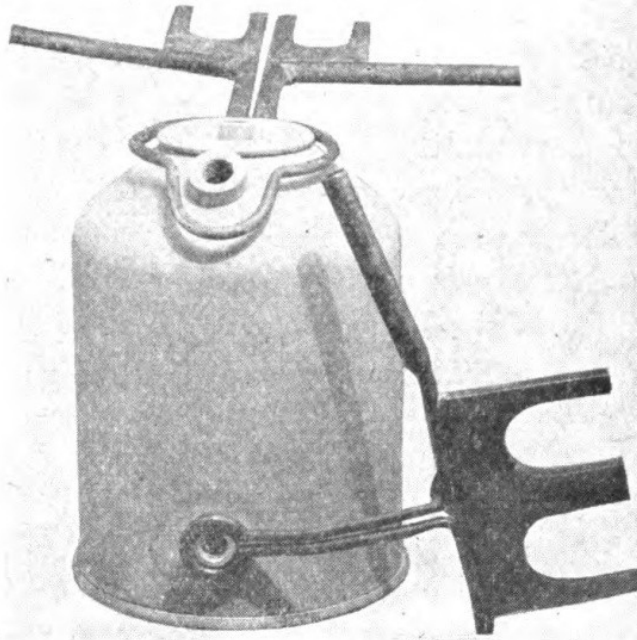

FIG. 106.—Various heating coils arranged for the soldering of steel inserts to a sheet-metal container. The upper coil is arranged to solder two inserts at one time.
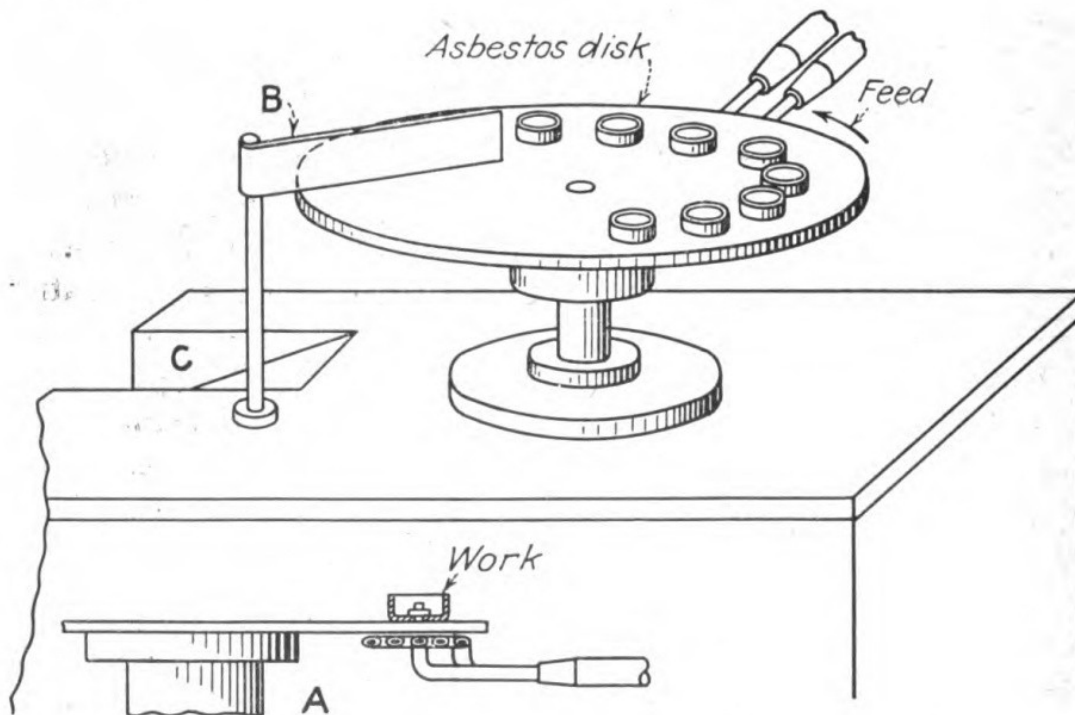

FIG 107.—A rotary-type induction-heating fixture which lends itself to a wide variety of soldering operations, especially for small, thin parts.

short time, so that it is often possible to use loosely coupled coils. More than in brazing, it is a case of avoiding overheating; there-

fore, for soldering, the coil can be spaced a little farther away from the work, as represented by the coupling and spacing of the upper coil.

Continuous Soldering. A turntable fixture for soft-soldering small parts is shown in Fig. 107. The work is placed on an asbestos disk, which is mounted on a slowly revolving spindle. As the parts pass to the rear over a pancake-type induction coil located under the disk, they become heated to the temperature needed to make the preplaced solder flow uniformly around the joint. A section taken through the coil and disk may be seen at
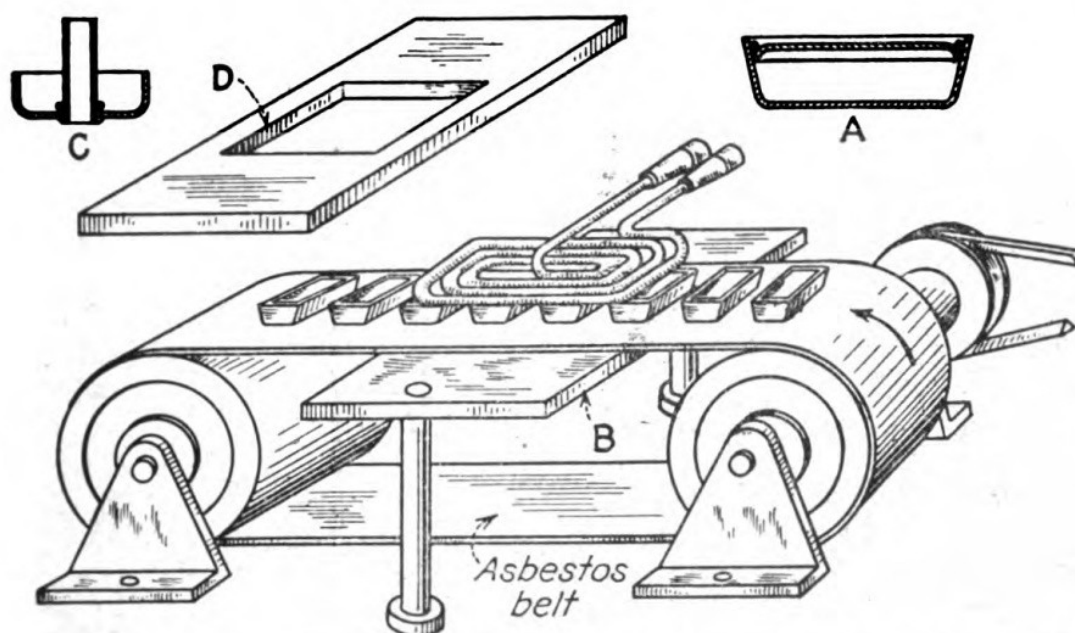
Fig. 108.—A continuous-feed fixture comprising an endless asbestos belt, used for induction-soldering operations. The coil can be placed on top of or underneath the belt.

A. After the work has passed the heating zone, it is ejected by means of the plate *B* and falls through the chute *C* into a tote box. A fixture of this design will find many uses in plants where much soldering is encountered. The drive to the spindle should be provided with a variable control to make possible correct heating for parts varying in size or shape. Such a design is also feasible for coils of different styles, so that the length of the heating zone can be made shorter or smaller as may be desired. The asbestos disk offers no resistance to the passing of high-frequency current, although if desired or if the part being soldered so requires the induction coil can be arranged on top, permitting the work to pass under it.

Another type of continuous soldering and brazing fixture is illustrated in Fig. 108. The part shown is a small condenser can A, to which a cover is being soft-soldered. A preformed ring of solder is placed on the cover and the assembly laid on the asbestos belt, which is power driven by a small motor and a variable-feed drive. A section of asbestos board B is placed under the belt to support it between pulleys. The pulleys are made of hard wood, so that there are no metallic parts close enough to the induction coil to absorb any of the high frequency magnetic flux.

As in the preceding example, this type of fixture is suitable for a variety of soldering operations through the application of different
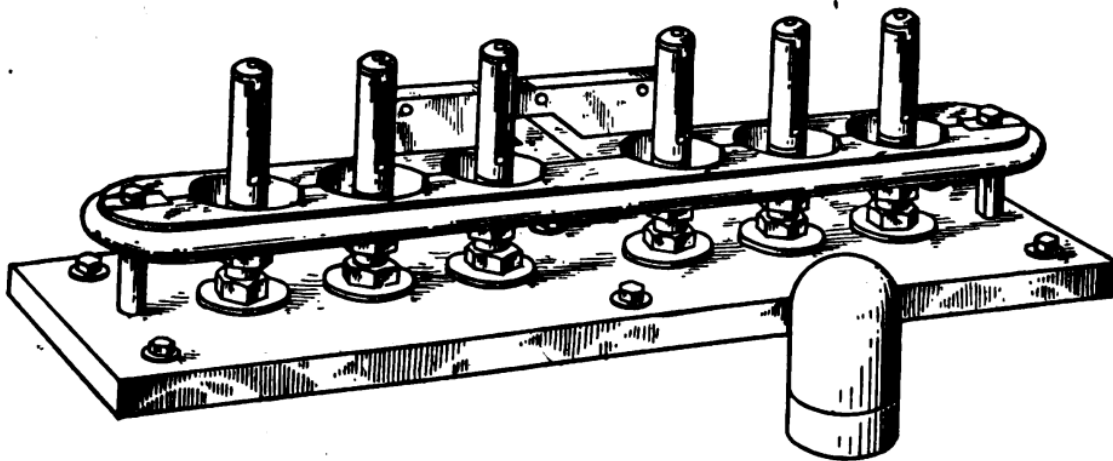
FIG. 109.—A series-type induction coil used for the brazing of six sheet-metal assemblies at one time. (*Courtesy of Induction Heating Corp.*)

coils and changing their location as needed. The part shown at C, for example, is better suited to heating from the bottom side. For this the asbestos board can be cut as may be seen at D, so that the induction coil can be set into it and thus induce the high-frequency current through the asbestos belt.

Multi-brazing Operations. In Fig. 109 is illustrated a simplified form of fixture and a series-type coil used for silver-brazing a sheet-steel dome to a steel base plate in which six pieces are jointed together simultaneously. The parts are prepared for brazing by assembling them with a ring of silver alloy at the joint, to which is applied a suitable quantity of brazing flux. In Fig. 110 may be seen details of the work assembly and its location in relation to the heating inductor, which is of the solid type made of a copper plate, bored as shown to provide a coupling about $\frac{1}{8}$ in. from the workpiece. The

plate is provided with saw cuts so that the high-frequency current follows the path of the arrrows, coming in at one lead and going out at the other. A copper-tube cooling coil is brazed around the outside edge of the inductor plate, the ends of which are attached to hose connections providing the water supply. The six assemblies are brazed in 30 sec.

A tandem-type coil used for brazing two assemblies at one time is illustrated in Fig. 111. The coil is made of a flat copper
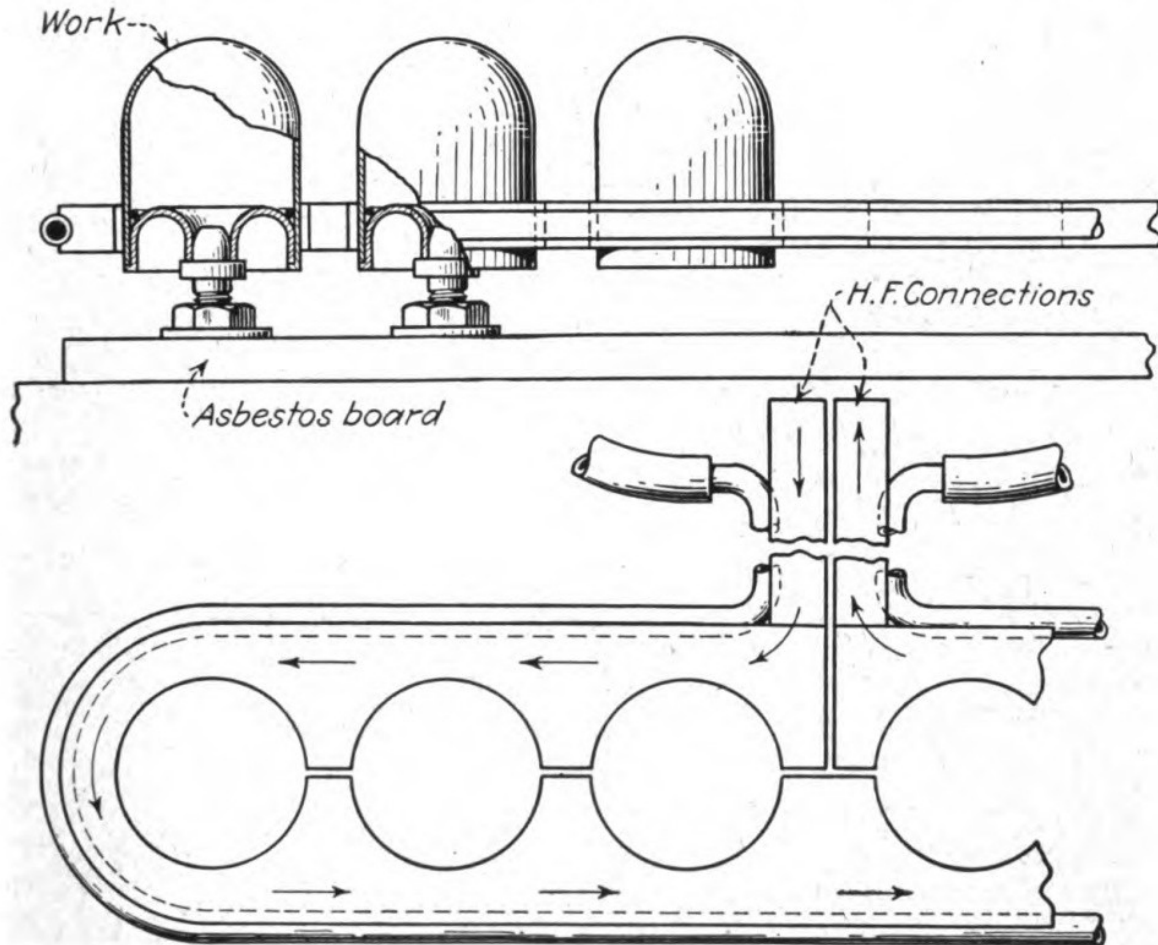

FIG. 110.—Constructional details of the coil and fixture used for brazing dome assemblies.

plate, bored out with two openings large enough to provide correct coupling from the work. This coupling is made to $\frac{1}{8}$ in. The plate is then slotted by a $\frac{1}{32}$-in. cutter, so that the high-frequency current will pass continuously around the openings. A single copper tube is then brazed on the outside to provide for cooling.

In operating the change-over switch used with two-station brazing or hardening tables, such as those shown, it is possible to actuate it by means of a solenoid, which in turn is controlled

by the master timer. In operation the solenoid is actuated immediately after the completion of the heating operation on one side of the table, so that the setup on the opposite side is automatically engaged, thus eliminating any manual work.

Vertically-operated Fixture. An example of a two-station brazing setup equipped with fixtures having air-operated elevating platforms is illustrated in Fig. 112. Here two parts are brazed simultaneously by a series-type coil of solid-inductor
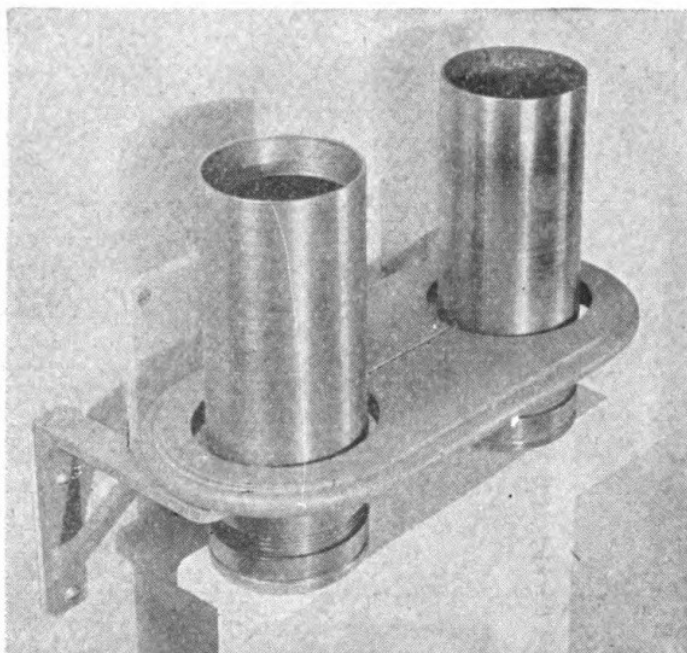

FIG. 111.—A solid-type inductor arranged to braze two tubular steel assemblies simultaneously. (*Courtesy of Induction Heating Corp.*)

design. On the table may be seen a flange and a sleeve which are brazed together, as well as the silver-alloy rings which are used as the bonding agent. Two assemblies are placed on the fixture platform while it is at its lowest position. Then, through operation of the air valve, shown at the left, the workpieces are elevated into the coil to the correct brazing position. While one pair of parts is being brazed, the other fixture, seen in part at the left, is being loaded. With this type of setup the generator is in almost constant service, its only down time being that required to throw the changeover switch and engage the start pushbutton.

Strength of Joints. There is a definite relation between the strength of a joint and the thickness of the alloying agent. Usually the closer the fit between the surfaces to be joined, the higher the tensile strength of the joint. This relationship is illustrated graphically in the chart shown in Fig. 113. The
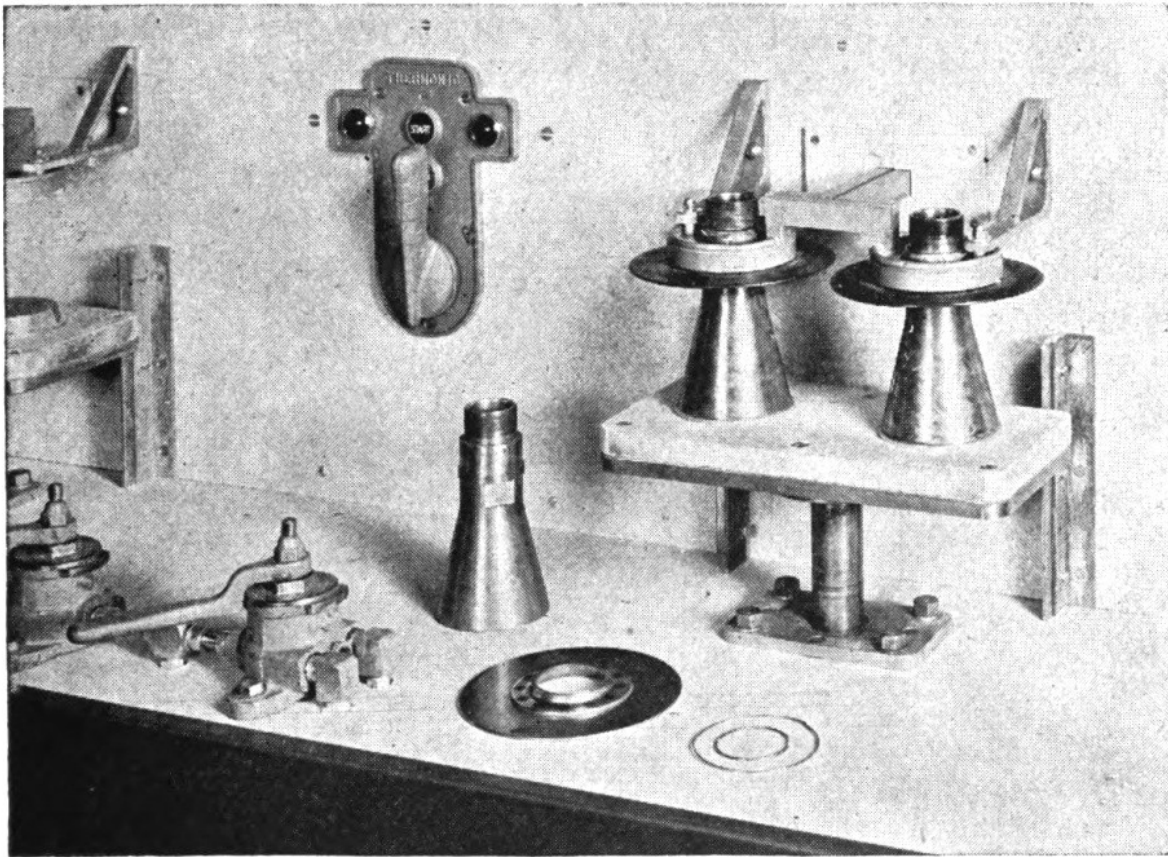
FIG. 112.—An induction-brazing fixture provided with vertically operated **work support, arranged for the brazing of flanges to a steel body.** (*Courtesy of Induction Heating Corp.*)
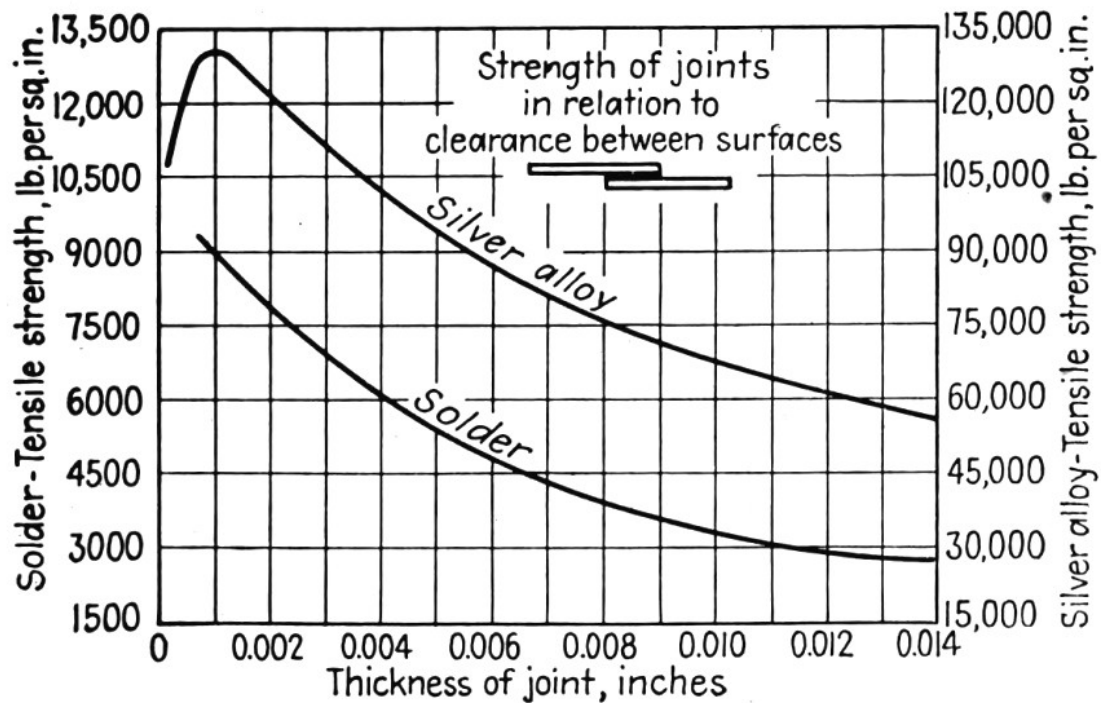

FIG. 113.—Theoretical strength of soldered and brazed joints in relation to the thickness of brazing alloy.

lower curve represents alloy-soldered joints, having clearances of from 0.001 to 0.016 in., for which the theoretical tensile strengths in pounds per square inch are listed in the left-hand column. Tensiles up to about 8,000 lb. can be obtained when the clearance or fit is held to 0.002 in. When the thickness of the joint increases, the tensile strength falls off until it reaches the strength of the solder.
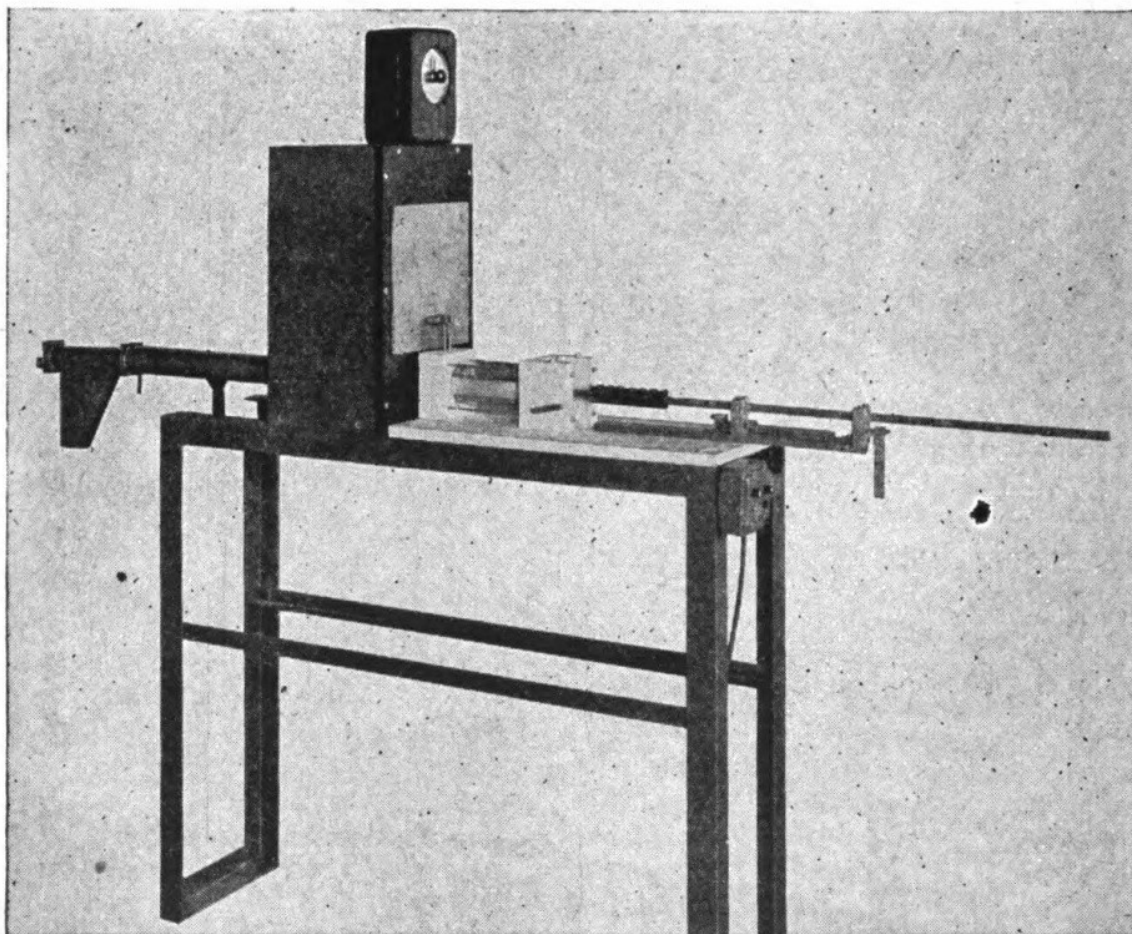
Fig. 114.—A continuous-feed fixture and coil used for the copper brazing of gun sights in a hydrogen atmosphere. (*Courtesy of Ecco High Frequency Corp.*)

The upper curve represents a silver-brazing alloy, for which the tensile-strength calculations are shown in the right-hand column. Silver alloys make it possible to obtain strengths above 100,000 lb. per sq. in., where the fit or clearance between surfaces is held to 0.001 to 0.003 in. As in the case of solder, the strength drops off as the thickness of joint increases to a point where it equals the tensile of the alloy. Thin films of silver alloy offer much more ductility than heavier sections and, of course, are stronger and more economical. Clearances below 0.001 in. often result in

bare spots, inasmuch as the silver alloy is unable to flow and, as shown on the curve, the strength of the joint falls off sharply at this point.

The figures represented in this chart are for tubular sections having uniform circumferential spacings, as well as for flat parts, where parallel surfaces are maintained. Usually with flat-surface soldering and brazing it is best to apply a slight amount of pressure to the joint as it heats, in order to force out excess alloy and thus assure a thin film, which offers the strongest joint.

Copper Brazing. A worktable and fixture for copper-brazing small gun sights are illustrated in Fig. 114. This brazing operation is carried out within a quartz tube, which is provided with a hydrogen atmosphere to prevent oxidation of the surface being joined. The parts to be brazed are fed over the rod shown at the right. Seven pieces are inserted into the chamber at one time. The coil is located within the quartz tube. Each group of parts requires a separate time cycle for brazing. After one group has been brazed, the door at the right is opened, and the next charge is inserted into the correct brazing position. This causes the previously brazed group to advance into a cooling chamber, which is located at the left. The operation is practically continuous and produces a total of three thousand pieces per day.
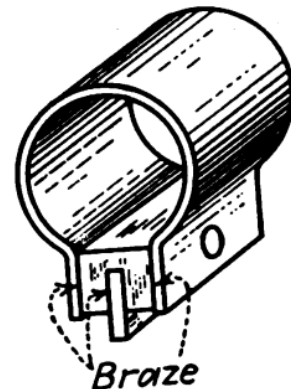

Fig. 115.—Constructional details of the gun sight which is brazed, as shown in Fig. 114.

The assembly comprises three parts, as illustrated in Fig. 115. These parts have been previously held together by a pin. The coil used is of the hairpin type and straddles the part at each side, so that heat is induced to the joints only. One of the advantages of brazing in a quartz tube of this type lies in the fact that the part can be observed during the brazing operation. The heating cycle, however, is automatic and is controlled by the timer shown at the upper portion of the panel.

A multi-brazing operation for joining a small tube and screw-machine flange is illustrated in Fig. 116. Twelve pieces are brazed simultaneously. The parts are located and centralized over a stud, mounted in the base of the fixture. Since the gener-

ator is used almost continuously, the only lost time being that required to throw the change-over switch from one station to the other, a setup of this type provides for maximum output.

Conveyor Soldering. A continuous-type setup for soldering covers on condenser cans is illustrated in Fig. 117. These condensers are completely assembled when soldered and comprise alternate layers of paper and tinfoil wound together. Preparation includes fluxing the bottom edge of the can body by dipping in a solution. A preformed ring of solder is then placed within
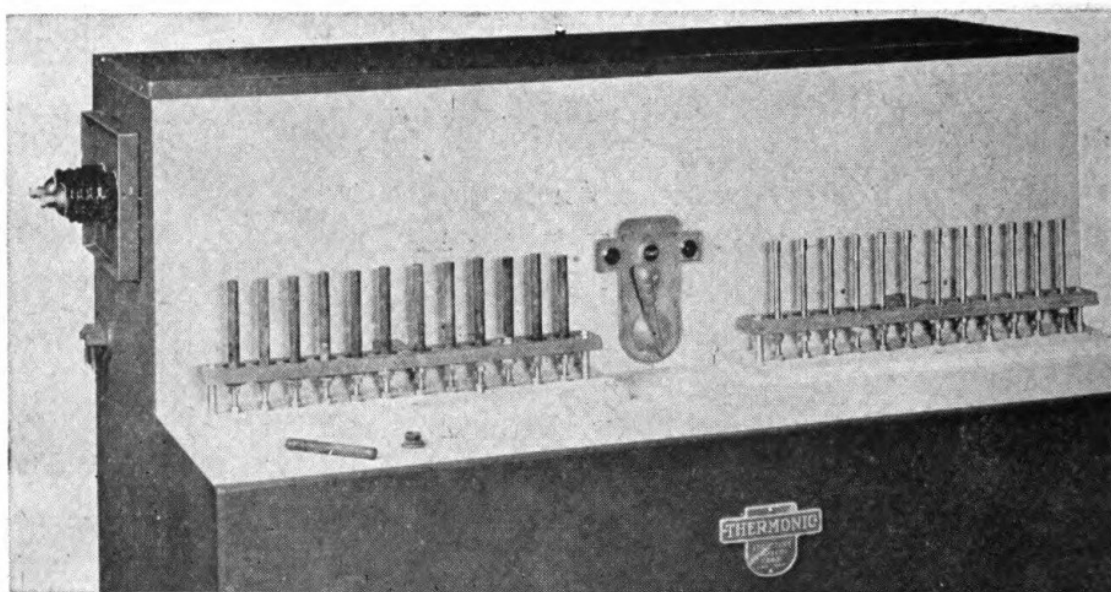
Fig. 116.—A multi-brazing setup arranged on a tandem worktable, so that one fixture can be loaded while the other is in use. (*Courtesy of Induction Heating Corp.*)

the cover, and finally the cover is assembled to the condenser body. The fit between both parts is important in order that a proper joint may be obtained.

With the assembly ready for soldering, it is placed on the conveyor and fed between inductors at a speed of approximately 10 ft. per min. As the work passes the inductor, the high-frequency current flows around the entire edge of the condenser assembly, causing the solder to melt and flow within the joint. The heat is inducted to the joint area only, and therefore the condensers cool rapidly after they pass the heating coils.

Because of the shape of the part, it is sometimes preferable to join one piece at a time, and in Fig. 118 is illustrated a coil used for the brazing of a Bourdon tube to a flanged casting. For this operation a focus-type inductor with a connected coil surrounding the entire surface to be heated is used. The heating coil is made
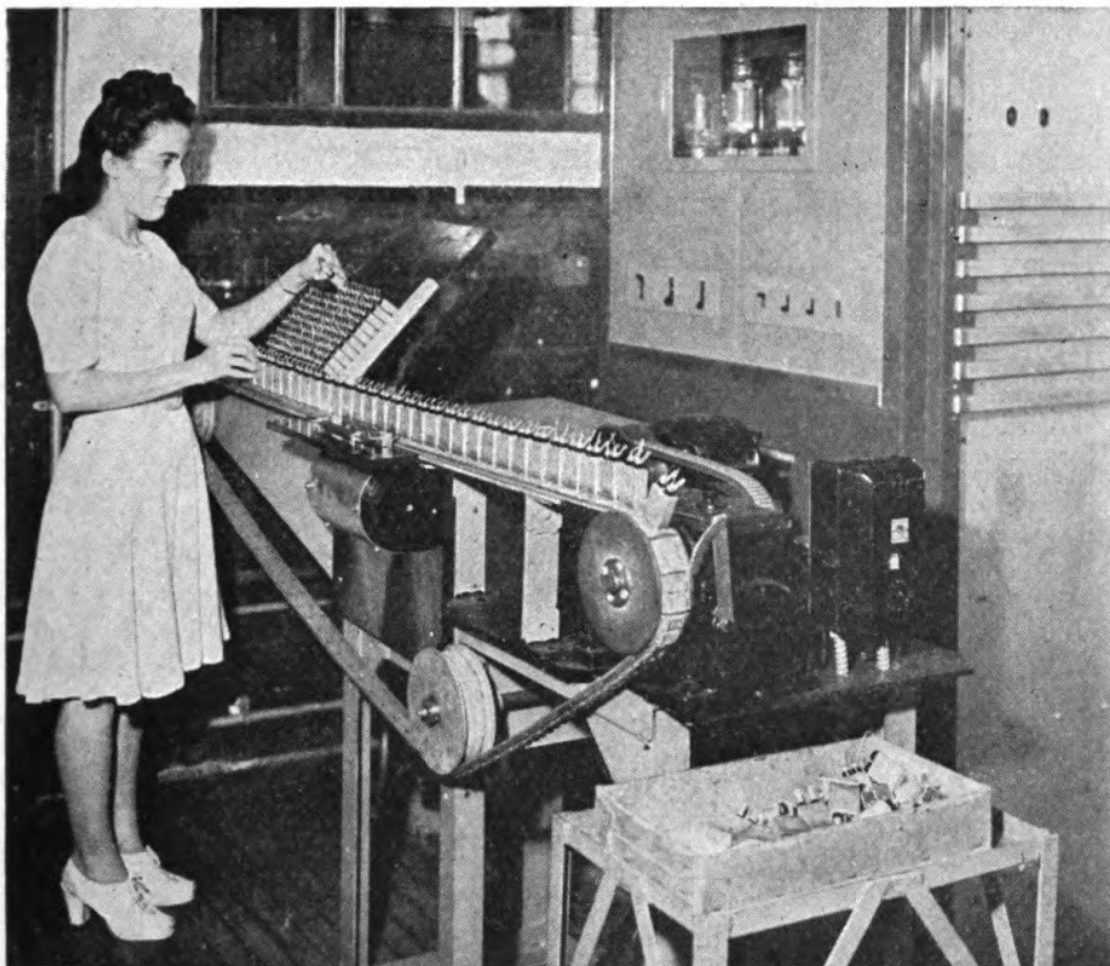
FIG. 117.—A conveyor-type feeding device as used for the soldering of condensers.
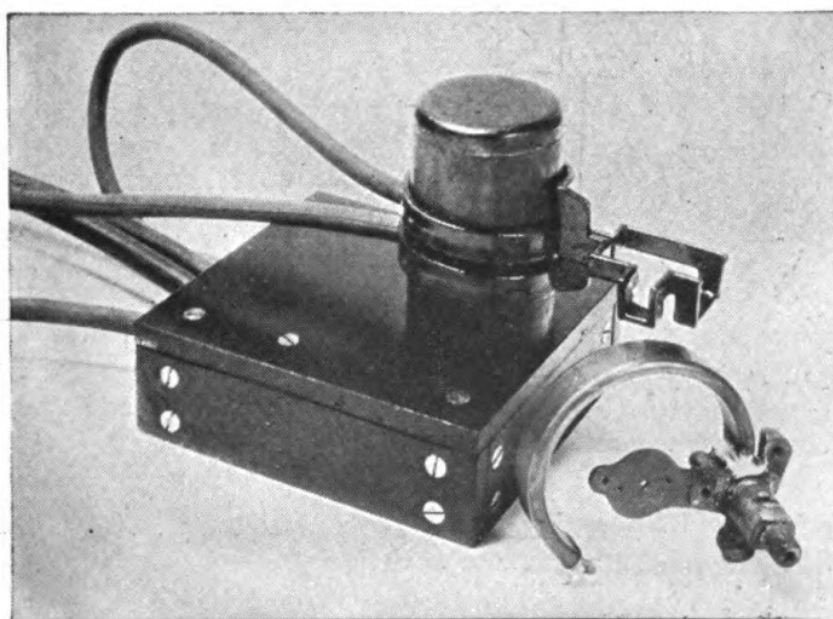(*Courtesy of Radio Corporation of America.*)

FIG. 118.—A single-turn heating coil, and focus inductor used for the soldering of
Bourdon tubes. (*Courtesy of Ajax Electrothermic Corp.*)

from a flat tubular shape of copper, so that water cooling can be maintained. A completely brazed assembly is shown at the lower right.

In Fig. 119 is illustrated a fixture used for soldering a series of plates to a shaft of a small variable-radio-trimmer condenser, by
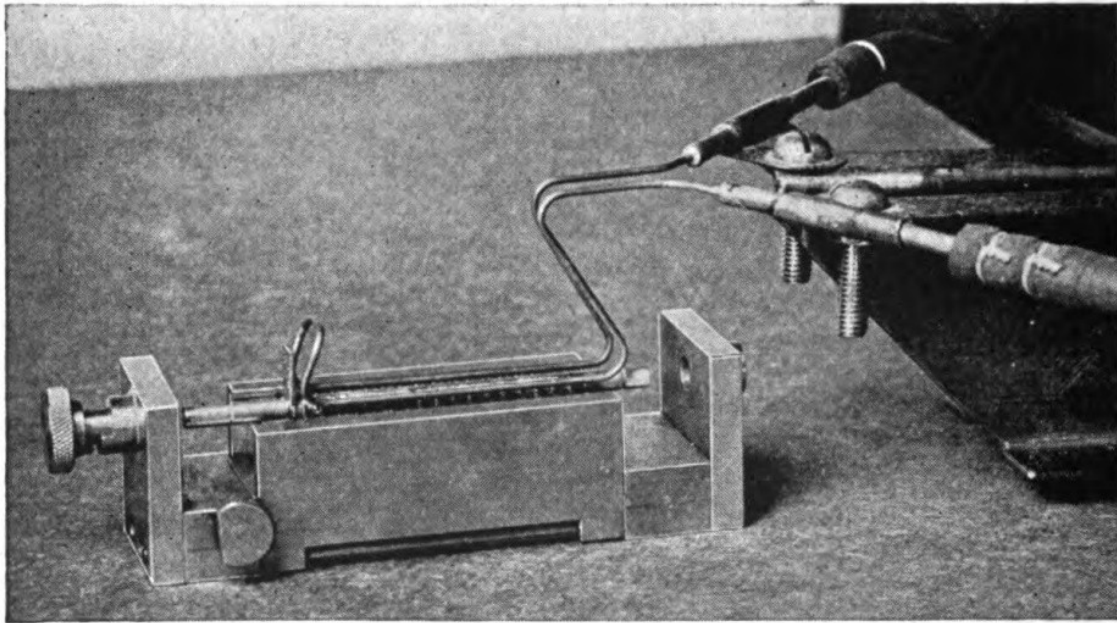
FIG. 119.—Soldering the plates of small variable condensers is carried out by means of this fixture and a single-turn heating coil. (*Courtesy of Federal Telephone & Radio Corp.*)
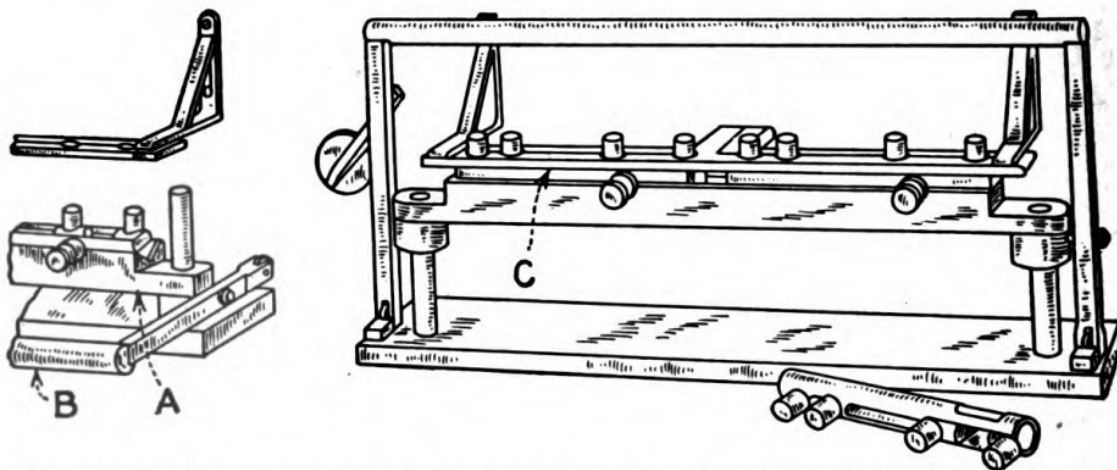

FIG. 120.—A fixture used for the brazing of four lugs to a receiver body. Two assemblies are brazed simultaneously, so that eight joints are completed at one time. (*Courtesy of Induction Heating Corp.*)

means of a single-turn inductor coil. The assembly is first placed within a fixture, and then a strip of solder material is placed on top. With the assembly in place, power is applied to the coil, so that the high-frequency current is induced into the shaft and

plates, heating them sufficiently to melt the solder, and to solder all joints at one time.

The fixture illustrated in Fig. 120 represents a setup for brazing four lugs to a cylindrical receiver body. A finished piece is shown at the bottom of the fixture on the right. The fixture is arranged to hold two pieces, so that eight joints are completed at one setting. The parts are assembled on to the fixture body when the locating plate is at its lowest position, as shown at the
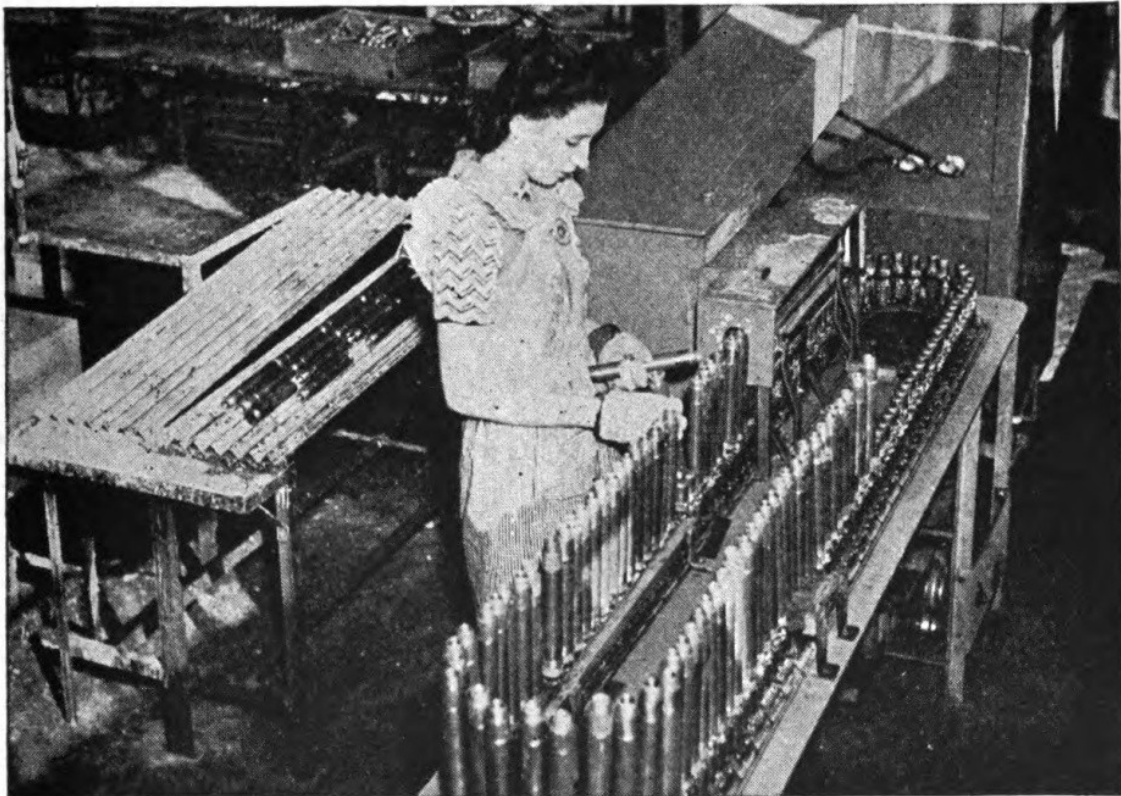

FIG. 121.—A conveyor-type brazing operation arranged for the joining of metal assemblies. The work is loaded and unloaded at the position shown directly in front of the housed heating coil. (*Courtesy of the Philco Radio Corp.*)

extreme right. By raising the crosshandle *A*, the workpieces are elevated so that the lugs are surrounded by the heating coil. The coil in this case is of the solid-series type, $\frac{3}{8}$ in. thick and formed out on the underneath side to clear the shape of the workpiece. A preformed ring of silver alloy is placed over each lug before the parts are placed on the fixture.

Continuous Feed for Brazing. An excellent example of a continuous-feeding mechanism, used in connection with the brazing of tubes, is illustrated in Fig. 121. The assemblies to be brazed are placed on a continuous conveyor that is arranged with a series of work-holding stations. The parts enter the compart-

ment shown in the center, where the induction heating coil is located. The parts are heated as they pass the coil and then make a complete circuit around the conveyor. This process provides sufficient time for cooling, so that they can be removed at the same position in which parts requiring brazing are loaded.

Induction heating is widely used in progressive-feeding operations for soldering, brazing, and hardening, in which various types of conveyors can be used. As a rule such operations should be arranged so that a variable speed is available, as well as a certain amount of adjustment to the heating coil. With this combination it is possible to make adjustments to compensate for
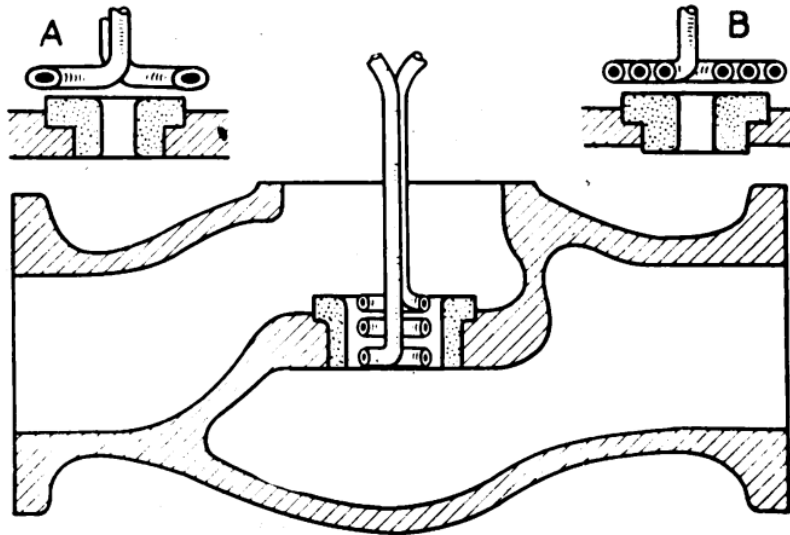

FIG. 122.—Various means of brazing inserts to valve bodies.

incorrect heating temperatures. For example, if during their travel the parts should become a little too hot in relation to the heating coil, the conveyor system can be speeded up slightly. On the other hand, if loading difficulties should make this procedure undesirable, the coupling of the coil might be increased slightly to reduce the generation of heat proportionately.

In Fig. 122 is illustrated a means of brazing alloy-steel inserts to cast-iron valve bodies. When the bushing is of sufficient size to permit the use of an internal coil, the setup can be made as illustrated in the center. The two leads coming from the coil should be kept very close together, however, so that there will be a minimum of heat losses along the flanged surface, where the leads enter the work.

Sometimes the insert of these parts is of such proportions that an internal-type coil cannot be used. In this case it is possible

to use a single-loop cylindrical coil, as illustrated at *A*. On the other hand, when the flange of the insert is wider, thus requiring a broader distribution of heat, it is possible to use the multiturn pancake coil shown at *B*.

The induction brazing of valve inserts, as illustrated, is more economical than the former method, which required heating of
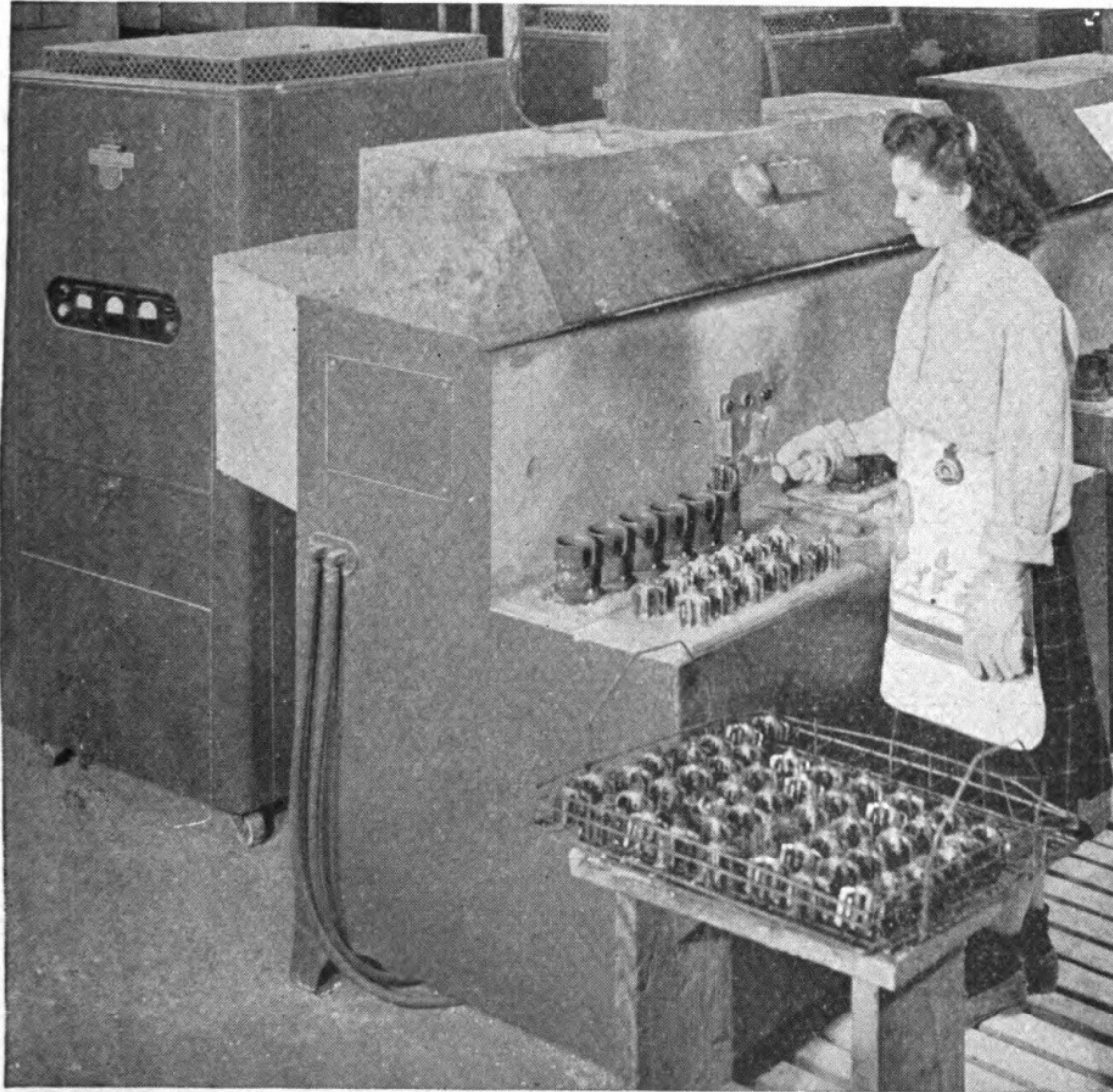

FIG. 123.—Induction-heating equipment used for the brazing of fins to a tubular hub. The brazing table is provided with two stations, so that heating is practically continuous. (*Courtesy of Induction Heating Corp.*)

the entire valve body. In operations of this kind, however, there are limitations and restrictions usually because of the shape and size of the part. However, with slight modifications in the design of valve, induction brazing is possible.

The setup shown in Fig. 123 is for brazing fins to a sleeve and is arranged so that six pieces are brazed at one time. Several of the fin assemblies may be seen at the front of the left-hand

fixture, and in Fig. 124 is shown a cross section through the coil and the workpiece. The coil is of the internal-hairpin type, over which the sleeve assembly is placed.

Each work-holding station is provided with a locating sleeve, for alignment of the assembly, to assure concentricity with the
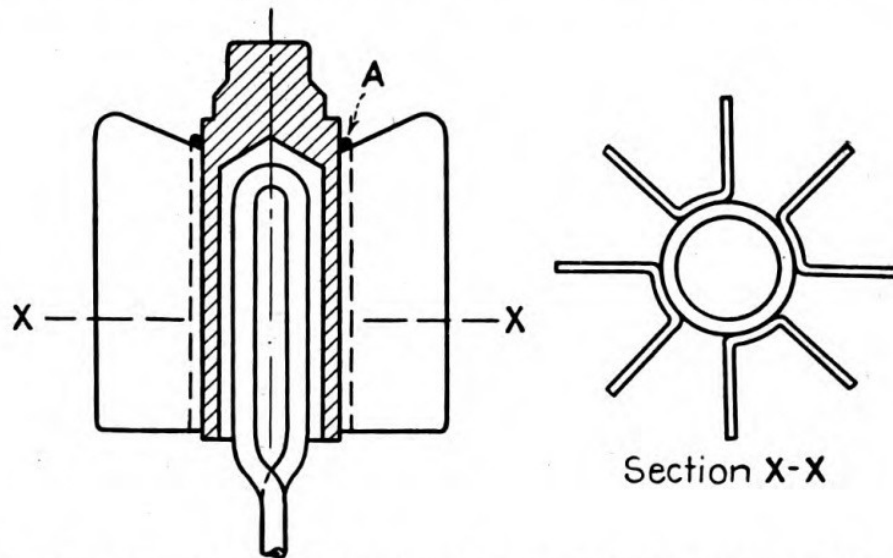

Section X-X

FIG. 124.—Constructional details of the fin assembly, together with hairpin-type coil, as used in the setup shown in Fig. 123.
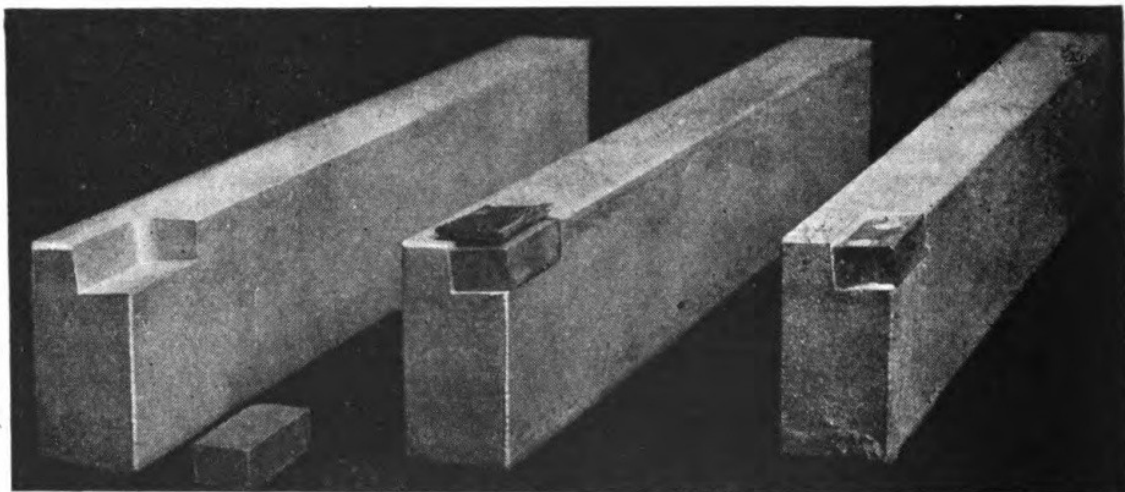

FIG. 125.—Steps carried out in brazing tungsten-carbide inserts to steel fins.

heating coil. The fins are spot-welded to the sleeve, as a preceding operation, to assure a firm metal-to-metal assembly. For brazing, a preformed silver-alloy ring is placed over the sleeve, as shown at *A*, so that when the assembly is properly heated the alloy flows throughout the joining surfaces.

Spot welding and induction brazing provide an excellent means of joining a large variety of assemblies, especially those that do not hold together by virtue of their construction. Many flat

assemblies can be joined by this combination method. Usually a small piece of silver wire, placed on top of or adjacent to the joint, will flow into the contacting surfaces by capillary action, thus producing an exceptionally strong bond.

Brazing of Tools. The application of high-frequency heat provides for a fast and dependable method for the silver-alloy brazing of tungsten carbide cutting tools. The process usually is carried out by forming a heating coil according to the shape of the tool and is so arranged that heat will be applied only to the area surrounding the joining surfaces. The coils used can be shaped in many ways and can be of the single-turn or multiturn
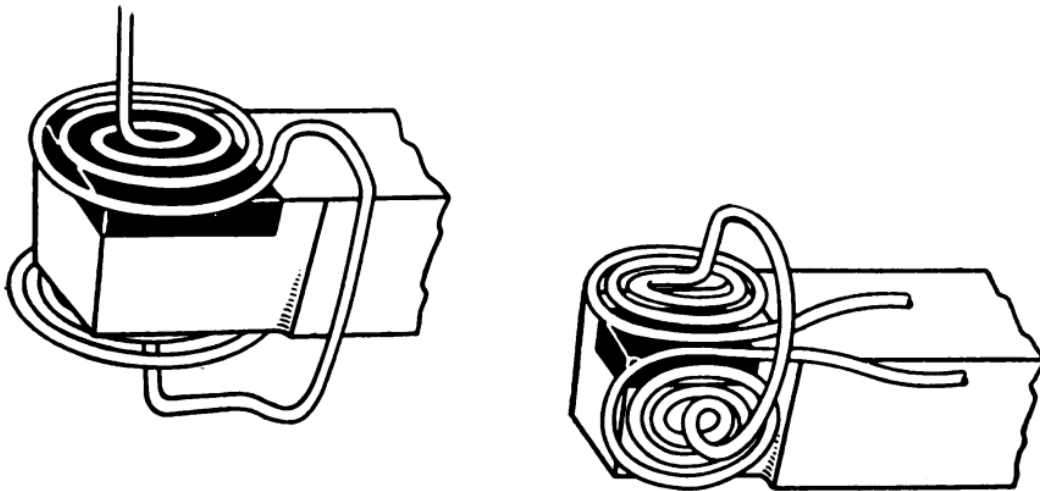

FIG. 126.—Two types of induction-heating coils used for the brazing of tungsten-carbide tools. (*Courtesy of Carboloy Co.*)

type, depending upon the size of tool. With single-shank tools, as illustrated in Fig. 125, the carbide tip and recess should be provided with a good fit; then, as shown in the center illustration, a piece of silver brazing material may be placed either on top of or directly under the tip. Shown at the right is a finished brazed tool.

In Fig. 126 are illustrated two types of series-wound pancake coils. The example at the left shows a coil positioned at the top and another underneath the tool, so that heat is generated throughout the entire end section of the tool. The coil at the right, however, is arranged so that heat is generated at the top and on one side, and results in a more localized heat pattern, directed to the tip and surrounding section of the shank.

It is possible also to use a coil like that illustrated in Fig. 127, which is of the formed type and which, as may be seen, surrounds

the area of the tool to be heated. Such a coil is sometimes referred to as a clamshell inductor.

One of the most practical ways to braze a single-point carbide-tipped tool is shown in Fig. 128, which represents the use of a single-loop heating coil. Here the coil surrounds the tip only, and when the tool is placed within the coil it is possible to press the tip firmly into place after heating, without having to remove it from the coil, as might be necessary with other types of inductors.

FIG. 127.—Multiturn coil of the clamshell type, which provides effective heating for carbide tool brazing.

The heating coil shown in Fig. 129 is of the formed type and is flat in shape, arranged so that it completely surrounds the area to be heated. A coil of this type is illustrated in Fig. 130, which also shows the various types of tipped tools that it can be arranged to handle.
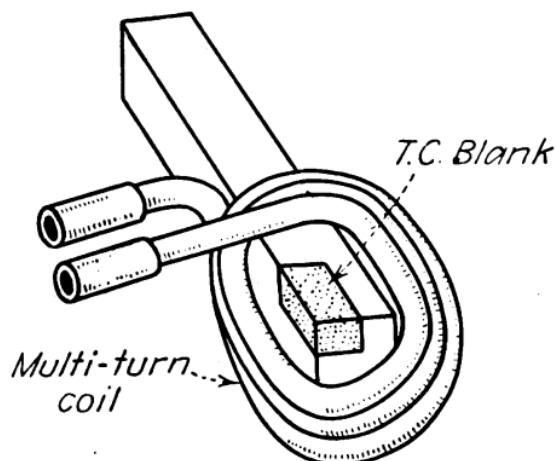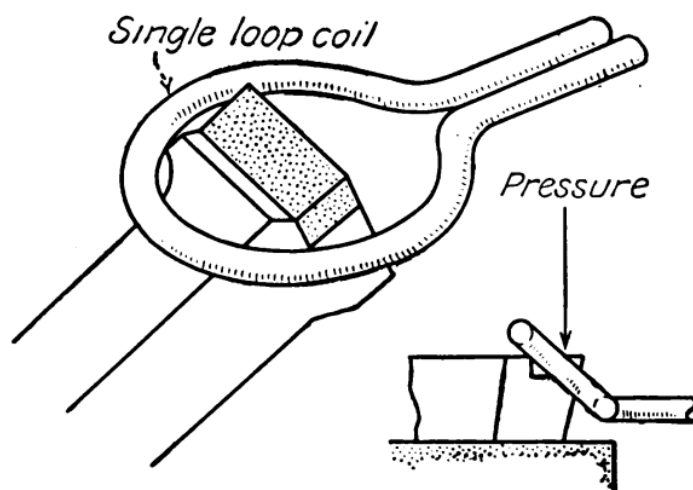

FIG. 128.—A single-turn coil used for brazing tungsten-carbide tools, which provides fast heating and also permits the tip to be pressed into place in the same position in which it is heated.

Another way to braze tools is by means of a multiturn coil which surrounds the entire end of the shank to be brazed, as illustrated in Fig. 131. In this method the tool is inserted into the coil and withdrawn after heating has been completed, so that as the alloy sets the tip can be pressed firmly into place.
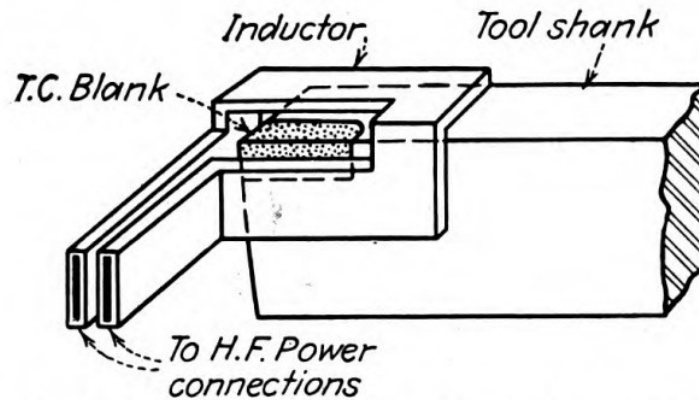
FIG. 129.—A single-turn induction coil of the formed type, which lends itself to a variety of tungsten-carbide tool-brazing operations.
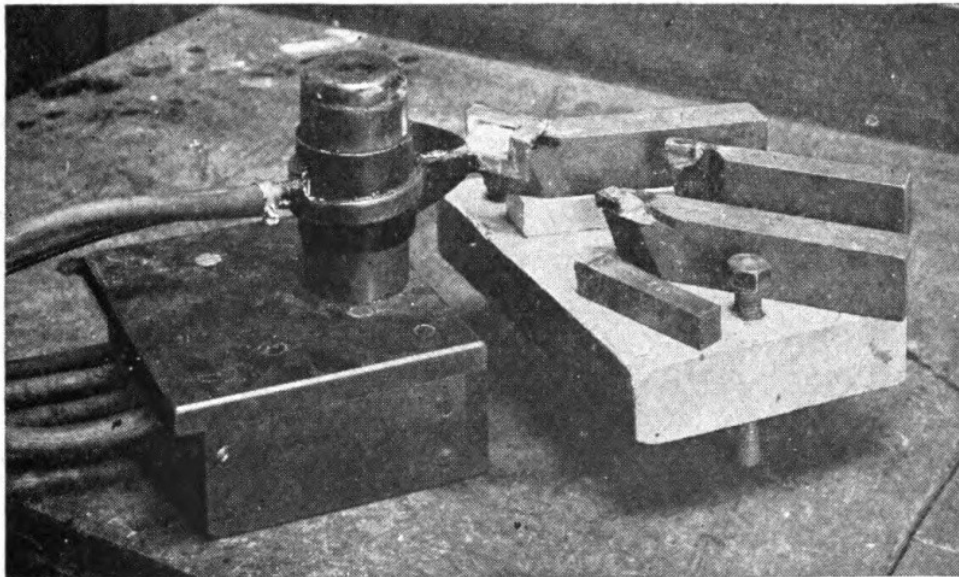

FIG. 130.—A formed heating coil used for the brazing of single-point tools. (*Courtesy of Ajax Electrothermic Corp.*)
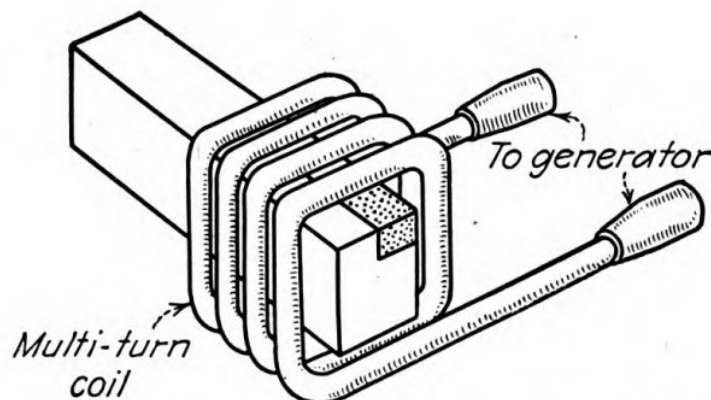

FIG. 131.—A multiturn coil commonly used for tungsten-carbide tool brazing. With this type of coil, the tool must be withdrawn when heated, so that the tip can be pressed into position.
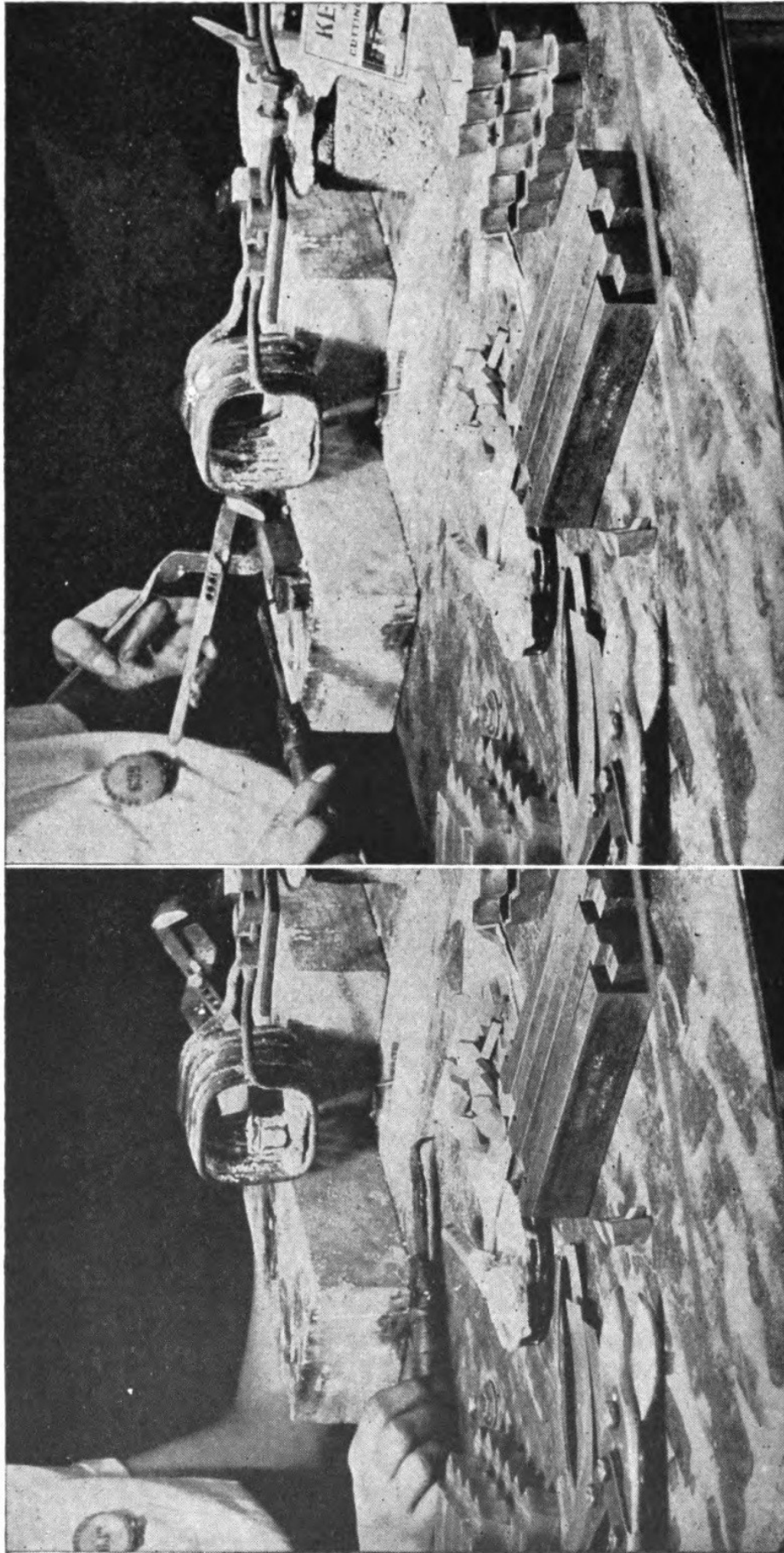
Fig. 132.—A production setup used for tool brazing. The illustration at the left shows the tool in the heating position, while at the right it is shown withdrawn from the coil for the tip-pressing operation. (*Courtesy of Kenna Metals, Inc.*)

This type of setup is illustrated in Fig. 132, which shows a straight-shank tool located within the heating coil, at the left. For this form of brazing, the heating coil can be more loosely coupled around the tool, because of the high intensity of the flux generated within the coil. As soon as the tool has become heated beyond the melting temperature of the silver alloy, it is withdrawn to one side, so that the tip can be pressed down into position to form a firm metal-to-metal contact while squeezing out any excess brazing material. This portion of the operation is shown at the right of the illustration.
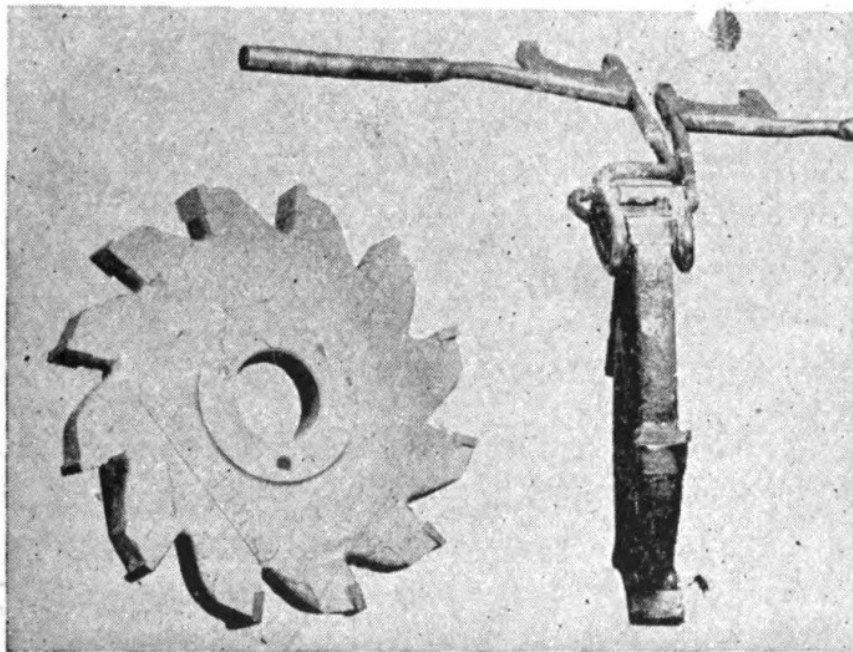
FIG. 133.—A double hairpin-type coil as used for the brazing of tungsten-carbide inserts to milling cutter bodies.

For the brazing of tungsten carbide inserts to milling cutters, such as that illustrated in Fig. 133, a copper-tube heating coil of the double-hairpin type can be used, so that heat is generated around the entire area of the tip and the adjacent area of the cutter body. With this type of setup each tooth is brazed separately.

In Fig. 134 are shown a variety of tungsten carbide–tipped tools, some of the single-shank type and others of the multi-blade type. One of these is the reamer shown within the coil at the upper section, which can be fabricated by induction brazing. With multi-brazing, such as reamers would require, it is necessary to hold the tips in place by wire or some other means, so that the inserts will be held firmly against the recesses of the cutter body during the induction-heating operation.

An example of the application of induction heat in tool brazing, in which an inert atmosphere is used, is illustrated in Fig. 135. This setup is arranged for the brazing of tungsten carbide–tipped reamers. The brazing operation is carried out by means of copper strip, which requires a melting temperature of about 2100°F. The heating coil is located around the outside of a cylindrical quartz chamber into which hydrogen is brought from the underneath side and burns off through the tube shown at the
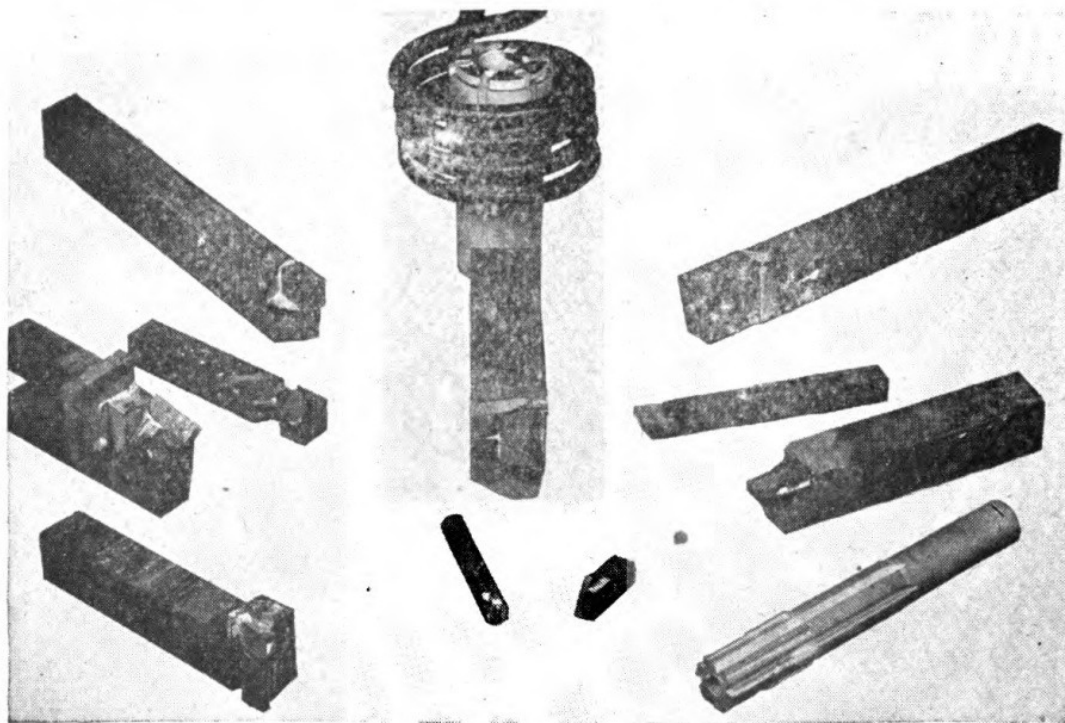
FIG. 134.—A variety of tungsten-carbide tools which lend themselves to induction brazing.

right. The use of the quartz chamber permits observation of the reamer during the heating cycle.

In some instances it is possible to copper braze by means of induction heat without the use of a controlled atmosphere, but usually such operations are limited to very small parts that heat up at exceptionally fast rates. Usually, however, the steel part being brazed develops a scale at temperatures exceeding 1800°F., with the result that the brazed surfaces become contaminated and will not produce a satisfactory bond.

Figure 136 show a high-frequency inductor, comprising two parallel bars, like those used for the soldering of condenser cans having an inserted-type cover. A preformed ring of solder *A* is placed around the inside joint, and when the inductor is energized
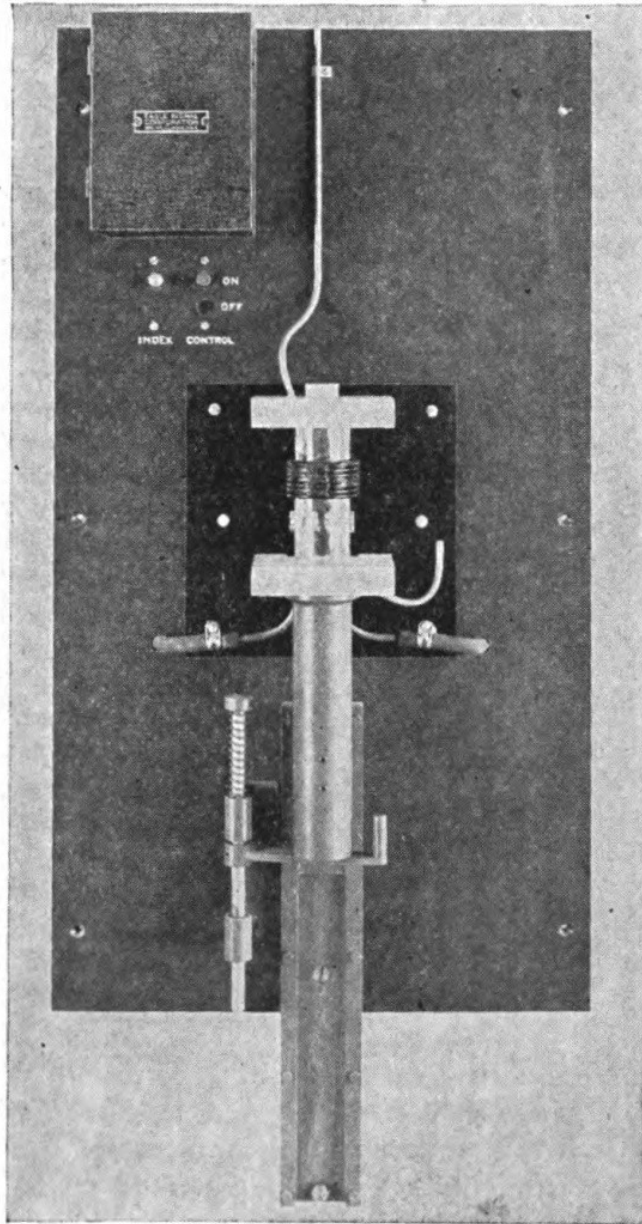
Fig. 135.—This setup shows a hydrogen chamber as used in connection with the copper brazing of tungsten-carbide reamers. (*Courtesy of Ecco High Frequency Corp.*)
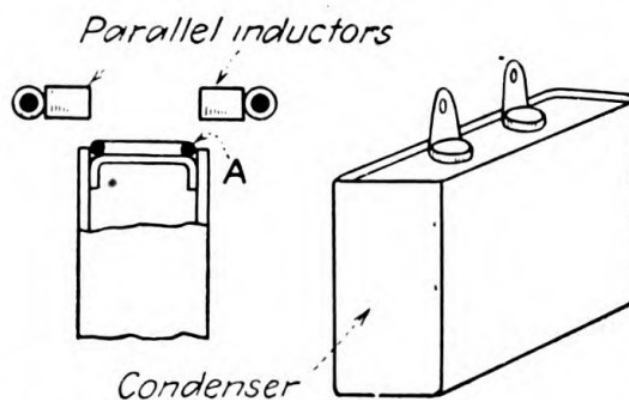

Fig. 136.—A typical parallel inductor, comprising two copper bars, as used for the soldering of covers on condenser cans.

heat is concentrated to the open portion of the assembly, causing the solder to flow into the joint and to provide a smooth, tight joint. For the soldering of parts, such as condensers, the work
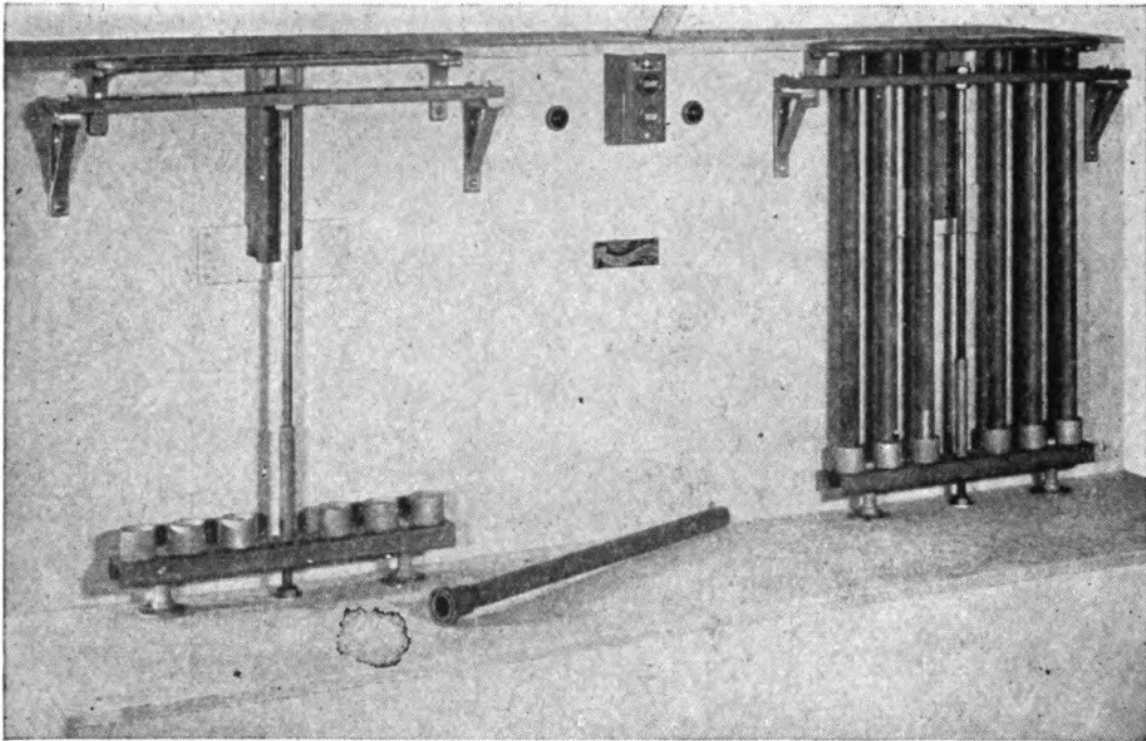

FIG. 137.—A tandem-type brazing table used for joining six tubes and flanges simultaneously. The heating coil is of the solid-inductor type and is located at the upper end of the tubes. (*Courtesy of Induction Heating Corp.*)

can be fed on a conveyor under the coil, as has been shown, or a series of condensers can be placed in a fixture having a vertical travel and then elevated to proper relation to a long heating inductor, comprising two parallel bars.
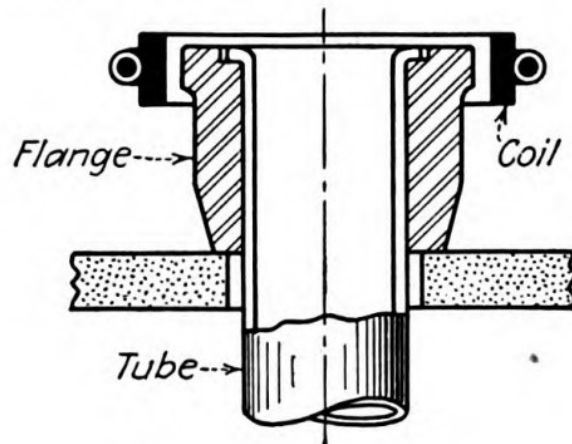

FIG. 138.—Constructional details of the tube-and-flange assembly, showing the relative location of the heating coil.

A setup for brazing six tubes and flanges simultaneously is

located at the uppermost section of the panel. The parts to be brazed are inserted through the coil and are located by means of a plate just below the coil. A sectional view of the upper portion of this assembly, showing the locating plate and the coil, are illustrated in Fig. 138. Alignment of the tubes at the bottom end is accomplished by cylindrical bushings, into which the tubes fit. The upper portion of the tube is flared out or beaded, so that it fits into the counterbore of the flange. A ring of silver-brazing alloy is placed at the joint and when the proper temperature has been reached flows freely through the area requiring joining.

CHAPTER V

HARDENING AND HEAT-TREATING

One of the principal uses of induction heating is in the hardening of steel parts, particularly where only localized surfaces require treatment. As with any other use of this means of heating, however, the shape of the part and the area to be hardened must be suited to this method of heat transfer. Parts requiring hardening all over do not usually lend themselves to induction treatment unless they are small in size or so shaped that a suitable heating coil can be properly proportioned to insure uniform heating. On the other hand, intricately shaped parts, which might be difficult to harden by other means, may be ideal for treatment by induction hardening.

There is no question that induction hardening is a rather selective means of heat treatment, and by no means is it intended to take the place of existing heat-treating techniques. It has its own field and will cover a rather broad range of hardening. Usually where induction hardening can be used, even with a choice of methods, this form of treatment has definite advantages. These are rapid heating with large production possibilities, uniform control so that rejections are minimized or eliminated, and, as a rule, economical heating costs, especially where only localized areas are heated. When heating is confined to localized surfaces, which might represent only a small portion of a relatively large part, deformation and warpage, so common with other forms of treatment, usually are eliminated. There is also, of course, no formation of scale, which often eliminates cleaning costs.

With high-frequency generators it is customary to have a hardening table with proper provisions for handling the quench, whether submerged or spray quenching is to be carried out. In Fig. 139 is illustrated a representative two-station hardening table provided with all the necessary features needed in the spray quenching of parts, such as gears, shafts, clutches, cams, and

other steel parts. This unit has two sets of terminal connections, so that one side of the table can be in use while the other is being set up for another operation.

There are two rotary-driven work-holding spindles, which can be engaged or disengaged as required. The table also is equipped with a multi-station electric timer, which provides for various

FIG. 139.—A two-station hardening table suited to the handling of a variety of work. Rotating spindles and a multi-stage timer are provided for automatic operation. (*Courtesy of Induction Heating Corp.*)

types of heating, quenching, and time-delay cycles. In gear work, for example, it is possible to provide for the necessary heat cycle, which can be followed by a slight delay if desirable, and finally to include the necessary duration of spray quench. Such a timer can also be used for the operation of solenoid devices or electromagnets, so that the heated part may be dropped for immersion quenching.

This hardening table also is equipped with an initial timer, so that the heating cycle required for a part can be recorded. For example, in setting up for a run of parts, the first piece is usually heated and the time checked for reaching the quenching temperature. With this time recorded on the initial timer, it is a simple matter to adjust the master timer so that subsequent pieces will be carried through in identical time. After the initial timer has served its purpose, it can be disengaged. The table is
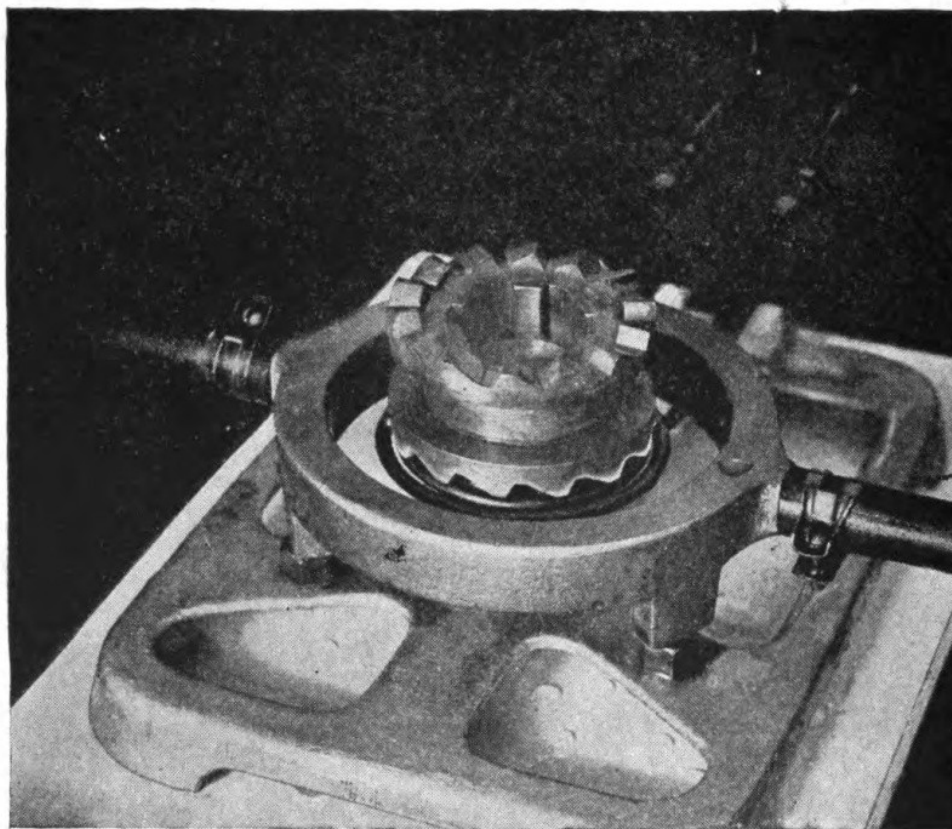

FIG. 140.—A fixture and heating coil used for hardening the teeth of a jaw-tooth clutch. The heating pattern on the face of the teeth can be seen.

equipped with a change-over switch located at the center of the upright panel, so that either hardening station can be operated as desired.

A fixture and coil for the hardening of clutch teeth is illustrated in Fig. 140. The clutch spool to be hardened is located on a stud, positioned at the end of the fixture, and provided with a flange, so that the surface of the work to be heated is held at correct relation to the pancake-type multiturn coil. Current is then applied, and the heat pattern follows the contour of the clutch teeth, as represented by the light band around them. This photograph was taken during the heating cycle and is representa-

tive of the heat layer obtained on a part of this type. At the completion of the heating cycle a spray quench is automatically engaged, by means of a timer and a solenoid-operated valve, so that the heated area immediately becomes hardened. In handling heating operations for parts of this kind, it is obvious that the part which becomes heated is the only area that is hardened. When automatic heating and quenching are applied, as in this example, uniformity of hardening is assured. The
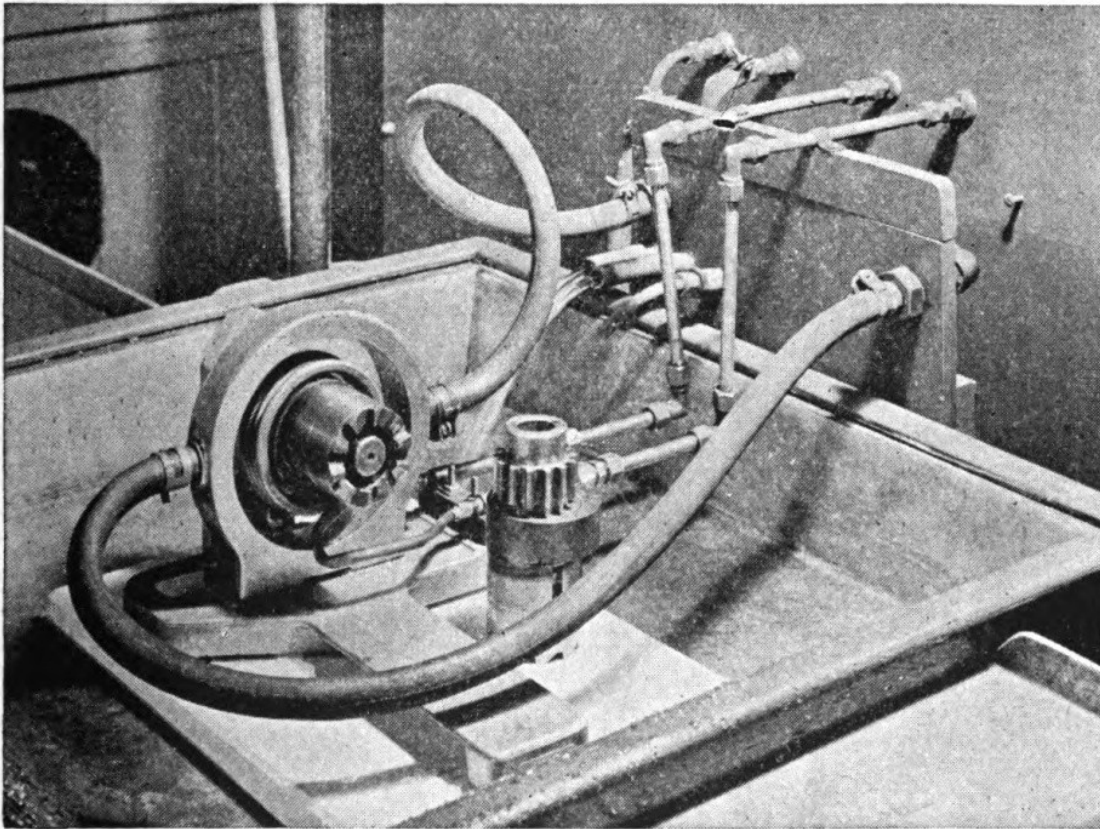

FIG. 141.—Fixture including quench ring and coil, as used for the hardening of the eccentric portion of a clutch gear.

hardening operation requires 14 sec., of which 8 sec. represents the heating portion of the cycle.

Another example of an induction-hardened part which is spray quenched is the gear shown in Fig. 141, made of S.A.E. C-1141 steel. Three separate hardening operations have been performed on this part, one each on the gear teeth, the clutch teeth, and the eccentric. One piece is shown in the fixture, arranged for the hardening of the eccentric surface, while another may be seen standing at right of the fixture. This is an unusual example of what can be accomplished with induction hardening, since the gear teeth are hardened to 52 Rockwell C, the clutch teeth to

between 55 and 57 Rockwell C, and the eccentric to between 60 and 62 Rockwell C.

The floor-to-floor times for the induction-hardening cycles are 18 sec. for the eccentric; 16 sec. for the gear teeth; and 13 sec. for the clutch teeth. A case depth of $\frac{1}{16}$ in. is provided for the clutch teeth and the eccentric, while a depth of about $\frac{3}{64}$ in. is produced in the gear teeth. No additional machining operations are required after induction hardening. The fixture assembly includes a base plate, a quench ring, a locating stud and holder, and the heating coil.
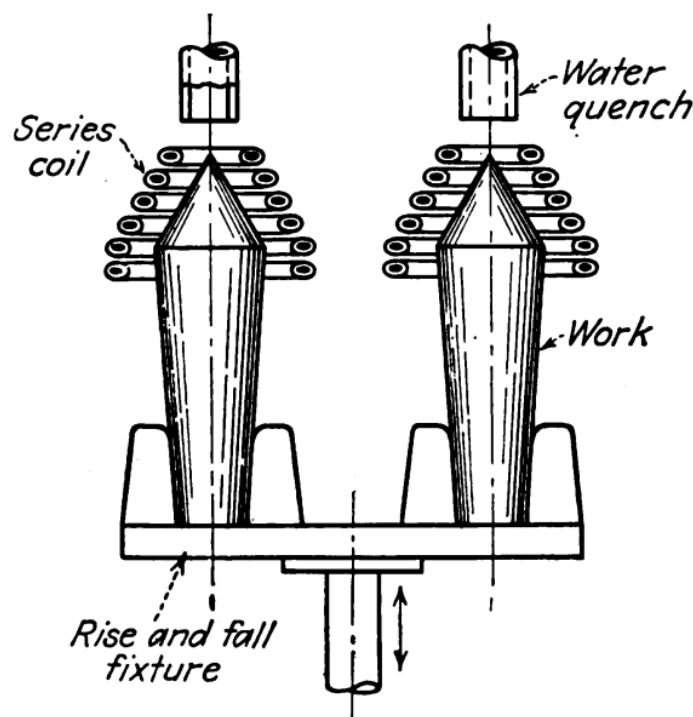

FIG. 142.—An elevating-type fixture used for hardening centers. A spray quench follows the heating portion of the cycle.

In Fig. 142 is shown a setup for the hardening of machine centers on which only the ends are required hard. As will be seen, two parts are placed on the elevating fixture, which, in turn, is raised to the heating position so that the tapered ends of the center enter the work coils. After obtaining the necessary heating, the current is turned off and the water quench is engaged to complete the hardening. The parts are then lowered and removed. This type of setup will be found useful in a broad field of heating applications, particularly where it is necessary to elevate the work into a coil, and where loading can be done more conveniently somewhat remote from the coil.

In Fig. 143 is shown a vertical-type induction-heating unit for the hardening of cam surfaces, gear, and bearings eccentric. In this setup two camshafts are hardened at one loading operation. After two of the cam sections have been heated and quenched the inductor is automatically raised one increment to bring the next two cams into the heating position, where the operation is
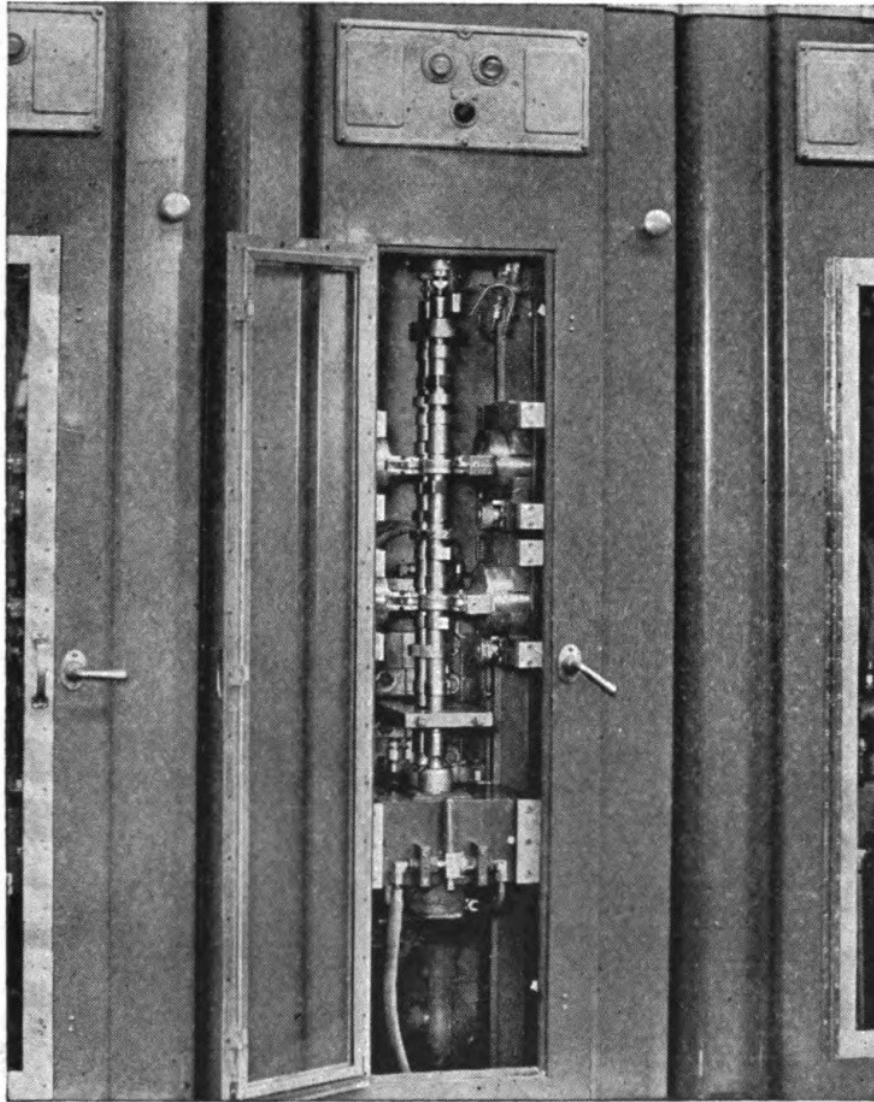

FIG. 143.—A setup for localized-hardening bearing surfaces of cam shafts. (*Courtesy of The Ohio Crankshaft Co.*)

repeated. The surfaces hardened follow the contour of the cams and a hardness of 60 Rockwell C is obtained. Usually camshafts of this type when hardened by other methods require straightening and cleaning operations. These, however, are eliminated as a result of selective hardening made possible by high-frequency generators.

In Fig. 144 is illustrated an induction-hardening setup for treating the bearing surfaces on automotive axle shafts. The

heating inductors are arranged in series one above the other, so that two shafts are treated simultaneously. These parts formerly required the use of inner hardened bearings, which were pressed on to the shaft; but by means of the induction-heating method it is now possible to localize-harden the shafts themselves so that they act as their own inner bearings, thus eliminating
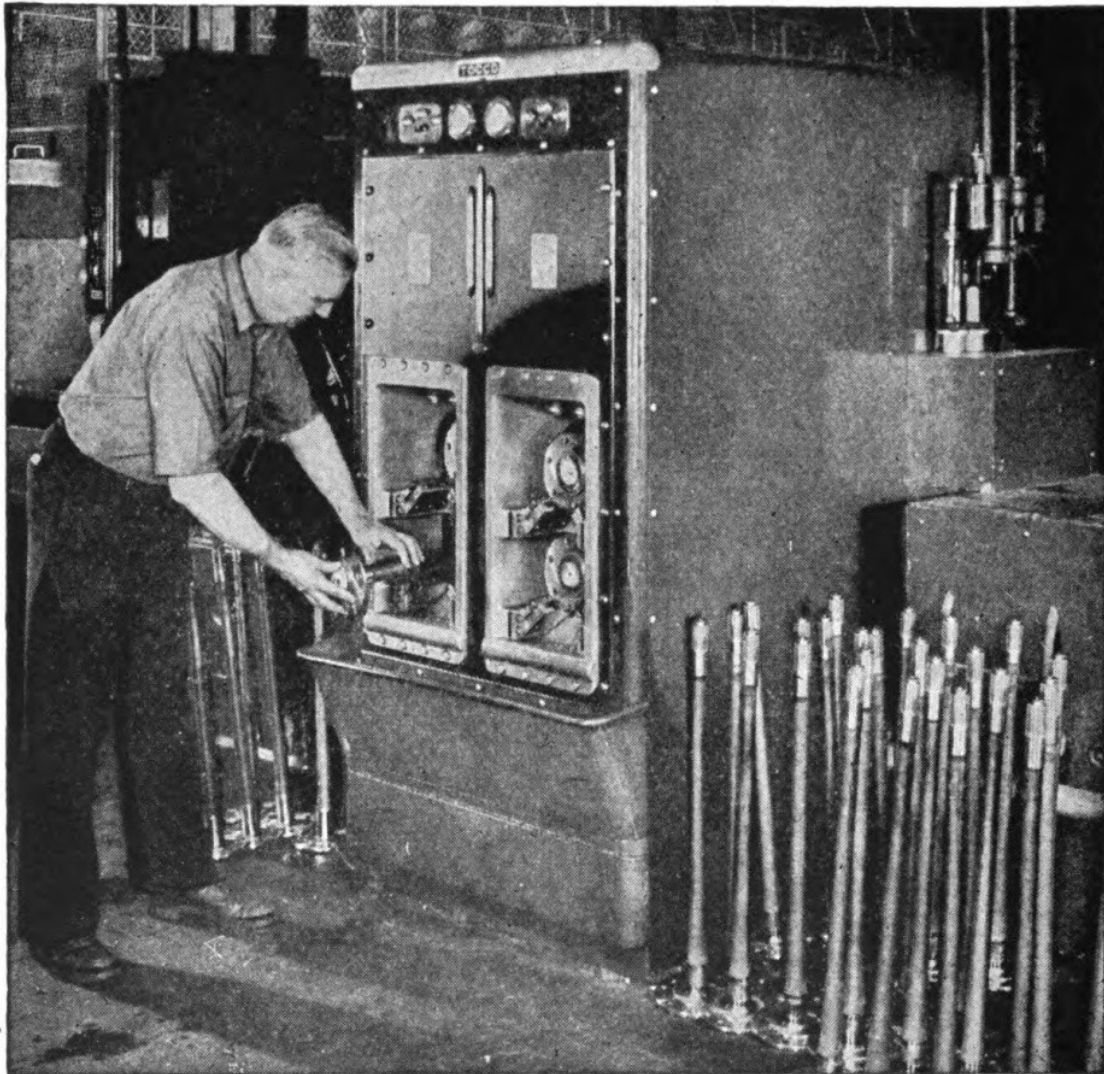

Fig. 144.—Induction-heating installation for hardening bearing surfaces on axle shafts, arranged so that two pieces are treated simultaneously. (*Courtesy of The Ohio Crankshaft Co.*)

the assembling of an additional part. Usually in applications of this kind the shaft can be made slightly heavier in design and still maintain a smaller over-all dimension than when a separate bearing is used. A change of this kind often results in increased strengths of 50 per cent or more.

An example of the advantage of being able to apply localized heat to a restricted surface is represented in Fig. 145, which

shows a standard form of thread-ring gauge. Gauges of this type usually are split and are likely to go out of shape when subjected to the normal hardening treatment. When this occurs, there is practically no way to straighten them, resulting in a loss due to spoilage. By means of high-frequency heat, however, the internal threaded section can be heated locally by a coil, like that illustrated, and after the proper heat has been attained the part can be dropped into an oil or water quench. Another advantage in hardening such a part by induction heating is the elimination of the usual heavy scale prevailing in other means of heat treatment.

Many other tools and gauges are suitable for induction hardening, and it is possible that changes in heating practices will develop with time. There will also be many possible changes in the hardening of jig and fixture parts, which in the past have been made of tool steel and hardened all over. Many of these parts can be replaced by those made of a plain carbon steel and locally

FIG. 145.—An internal coil used for hardening thread gages. Heating is localized to the threaded area so that distortion is minimized.

hardened by induction heat on the surfaces only where resistance to wear is required.

When induction-hardening internal surfaces, where the length of the hardened area exceeds the diameter, it is preferable to use progressive heating methods arranged so that only a small area of the surface is heated at one time. This method is illustrated diagrammatically in Fig. 146. The work is mounted on an elevating platform, which feeds downward as the surface is progressively heated. Directly below the internal-type coil is located a pressure-spray quench ring, which applies a water quench to the surface immediately after it is heated. Rings for this purpose should be made of a nonmetallic material, such as plastics. Since the heat is localized at only one portion of the work, there is little chance of distortion and warpage, which
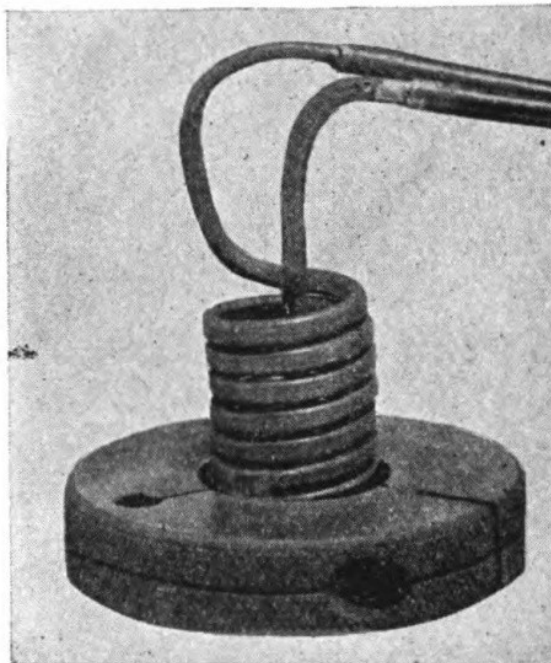
ordinarily might be experienced on parts such as those shown, heated by other methods.   In providing devices of this kind, it is desirable to include a variable-feed mechanism so that the rate of travel can be selected to suit the nature of the part being heated.

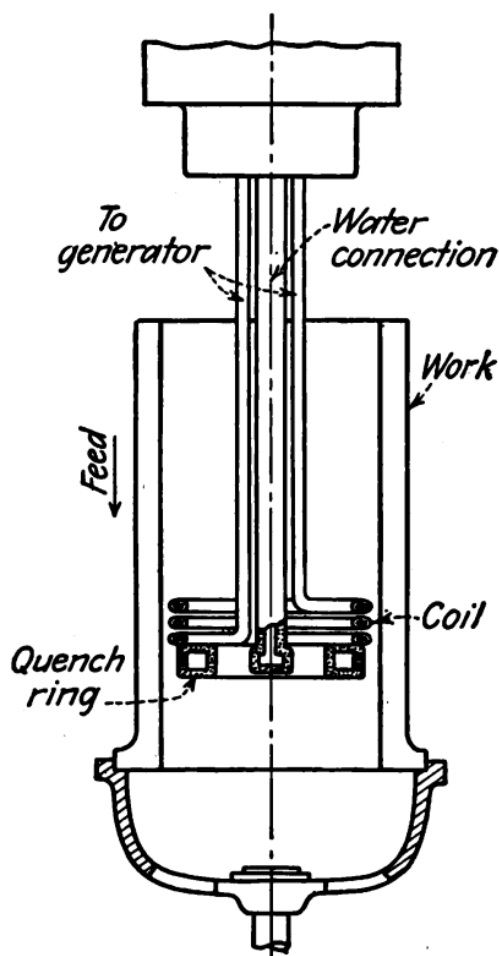Plastic quench rings for setups of this kind can be made of a liquid resin, mixed with a proper amount of accelerator to produce the design shown in Fig. 147.   The procedure is to make a wooden pattern around which is cast a mixture of plaster of Paris.   With the pattern removed, after setting, the plaster forms a mold into which the liquid resin can be poured.   A core, preferably made of metal, is assembled in the mold, so that a
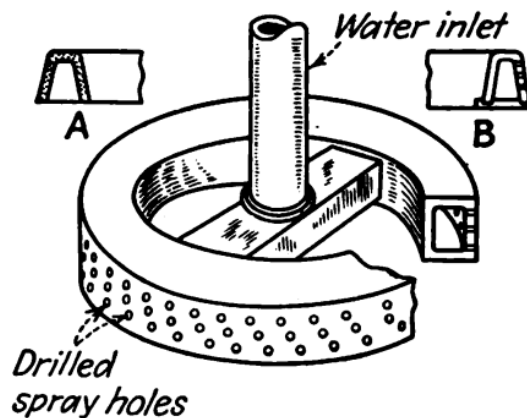

FIG. 146.—Internal surfaces can be heated and quenched progressively by feeding the work past the coil.

FIG. 147.—Constructional details of a cast plastic quench ring, which can be used in progressive internal heating.

shell-type ring, as shown at *A*, is produced.   The cover is molded to the quench-ring shell afterwards, to form the final section, shown at *B*.   This is done by setting the shell into another shallow mold in such a way that the edges are submerged into the liquid resin.

From this procedure it will be seen that two curing operations are required—one to set the shell and the other for applying the cover.   Commercial liquid plastics are available, which can be cured in 4 to 5 hr. at a baking temperature of 180 to 200°F.

Some liquid plastics air-harden in 24 to 48 hr., but the low-temperature baking usually is preferred. The rebaking of the shell, for molding the cover plate to it, does not affect the previously cured member.

Sometimes it is necessary to harden long bars, where progressive heating is required. A representative method is shown in Fig. 148. The bar to be heated travels on rolls located on each side of a sink, and is fed through a heating coil and finally through the spray-quench ring shown at the center. The bar is fed by the rollers *A* and *B*, which are power driven. By varying the speed rate of these rollers it is possible to obtain different feed rates in proportion to the size of the bar being hardened and the available power of the high-frequency generator. An operation
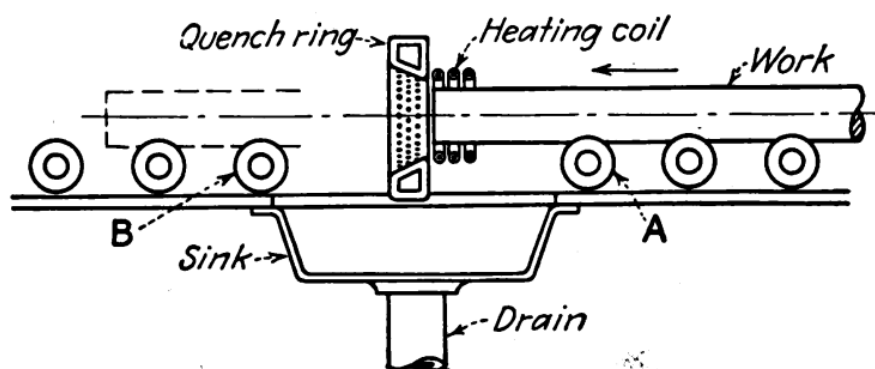

Fig. 148.—A setup used for the progressive hardening of a steel bar. The work feeds from right to left, and the heated surface is quenched immediately after it leaves the induction coil.

of this kind is useful when the outer surface of a bar requires toughening to resist wear and normal scuffing.

The use of solenoids and electromagnets in induction-hardening operations is often desirable. In Fig. 149 is shown a simplified form of setup in which the workpiece is suspended in a coil by means of a magnet. The magnet is connected to a timer operating the control cycle, so that the current is released as soon as the heating cycle has been completed. The work, which in this case is a small spline shaft, then immediately drops into the quench tank, located directly under it.

Gear Hardening. High-frequency induction heating is excellent for the hardening of gears. Even though restricted to certain types and sizes of gears, the process, when possible, gives exceptionally fast heating, with uniform results.

High-frequency induction hardening will have some effect on the types of steels used for the making of gears. Heretofore

there has been a broad use of alloy steels, usually as a means of obtaining a specified hardness. However, the indications are that a regular carbon steel can be used successfully for a wide variety of gears, and when only hardness to resist wear is desired, the use of alloy steels can possibly be materially reduced. For example, S.A.E. 1045 steel is suitable for induction-hardened
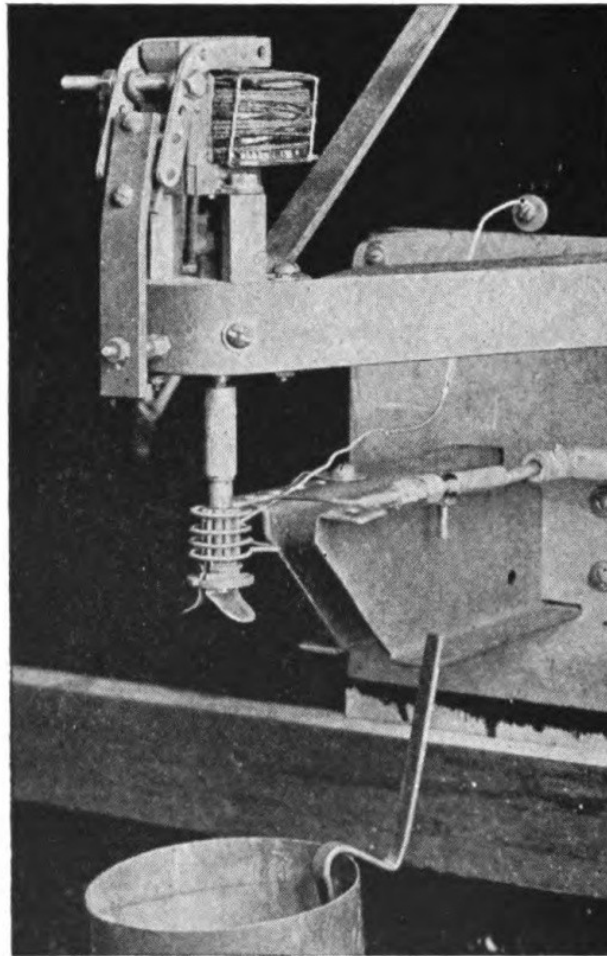

Fig. 149.—The piece being heated is suspended by means of an electromagnet, which automatically releases the part after heating has been completed. (*Courtesy of Federal Telephone & Radio Corp.*)

gears, and surface hardnesses up to 60 Rockwell C can be readily obtained.

Another grade of steel that has proved suitable for induction hardening is S.A.E. C-1141. This steel has free machining qualities and has been used successfully in the manufacture of a wide variety of gears. Other steels are available, which, having a minimum yield point of 100,000 lb. per sq. in. and a carbon content of from 0.45 to 0.50 per cent, will prove suitable substitutes for some of the alloy steels.

Induction hardening will also produce some changes in the processing of gears. In the first place, a steel with a higher carbon content usually can be substituted for a carburizing steel, thus eliminating carburizing. A steel with 0.40 to 0.50 carbon is but slightly more expensive than the same type with a low carbon content. Therefore, if surface-hardening of the teeth can be accomplished without carburizing, a worth-while saving results. The average cost of carburizing is $0.04 to $0.08 per pound, whereas the cost of a steel with higher carbon content is only $0.003 per pound.

A comparison of costs for a gear on which only the teeth are required hard, as illustrated in Fig. 150, shows a saving of 43
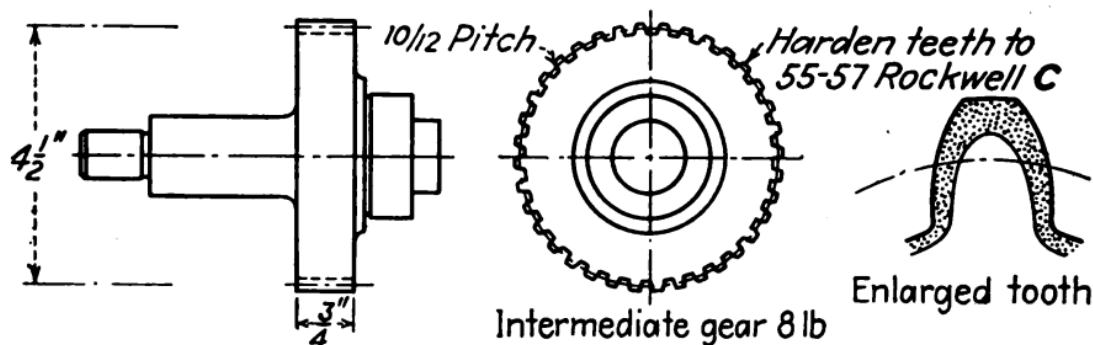
Cost and operation	S.A.E. 1020 carburize	S.A.E. 1045 induction
Cost of steel..........................	$0.40	£0.43
Carburizing at 0.039 per lb...........	0.319	
Cost of heat to harden...............	0.041	0.01
Cleaning..............................	0.02	
Total cost......................	0.78	0.44
Saving................................		0.43 %

Fig. 150.—Comparison of costs between a carburized-hardened gear and an inductively treated gear made of a higher carbon steel.

per cent through the use of the high-frequency induction-heating method. The cost of steel for the gear when made of S.A.E. 1020 carburized, as against S.A.E. 1045 induction hardened, was $0.40 against $0.43; carburizing at $0.039 per pound was $0.319 against zero; heat to harden was $0.041 against $0.01; cleaning was $0.02 against zero; and the total cost was $0.78 against $0.44—a saving of 43 per cent for the induction-hardened part.

The analysis includes the cost of steel in both cases, because this difference is related to the carburizing and induction-hardening costs. While there is only a fraction of a cent per pound difference in cost between the high- and low-carbon steels, the carburizing cost runs about 0.04 cent per pound. The cost of heating differs, too, since only a portion of the part is heated when induction hardening is applied, and the operating cost of the unit is comparatively low. A gear of the type shown can be heated, ready for quenching, in 17 to 20 sec., using a generator having 20 kw. output.

Gear-hardening Methods. In applying high-frequency induction heating for the hardening of gears and sprockets, where only localized heating and hardening is required, either of two methods may be considered. One is the immersion quenching into a tank of the heated pieces, and the other is the spray quenching of the part while it remains in the heating coil. The choice lies largely in the requirements of the piece to be heated, and sometimes can be made only after making analyses of both methods.

For immersion-quenching setups a variety of methods can be used. Some can be made semiautomatic, while others work best by manual control. Parts can be suspended into an induction coil by means of electromagnets controlled by timers, which release the part after a predetermined heat cycle has been concluded. Solenoid-operated trips and releases also can be utilized in connection with automatic timers, dropping the work into a quench as may be desired.

With spray quenching it is often possible to obtain the desired hardness more effectively than by other methods, since a slight variation of the heating or quenching times will vary the Rockwell hardness readings proportionately on a given surface. With immersion quenching this is not possible, and if this method is used it is often necessary to draw a part back to the required hardness.

Assuming a 3-in. diameter, 0.50 carbon steel gear requires hardening on the teeth only, a water-spray quench being used, a hardness of 60 Rockwell C can be obtained easily by applying a normal heating cycle and a suitable quenching period. If only 55 Rockwell C is wanted, however, the duration of quench is proportionately reduced to obtain this hardness. The part, likewise, is not thoroughly cooled so that the remaining heat acts

like a drawing operation. This difference in high-frequency hardening practices is mentioned since it will have a direct influence on the method to be used, and consequently on the type of fixture to be provided.

Gear Fixtures. A representative type of spray-quench fixture for hardening a spur gear is illustrated in Fig. 151. For this method a table with a built-in sink and a suitable drain is required. The gear is mounted on a stud which, in turn, is
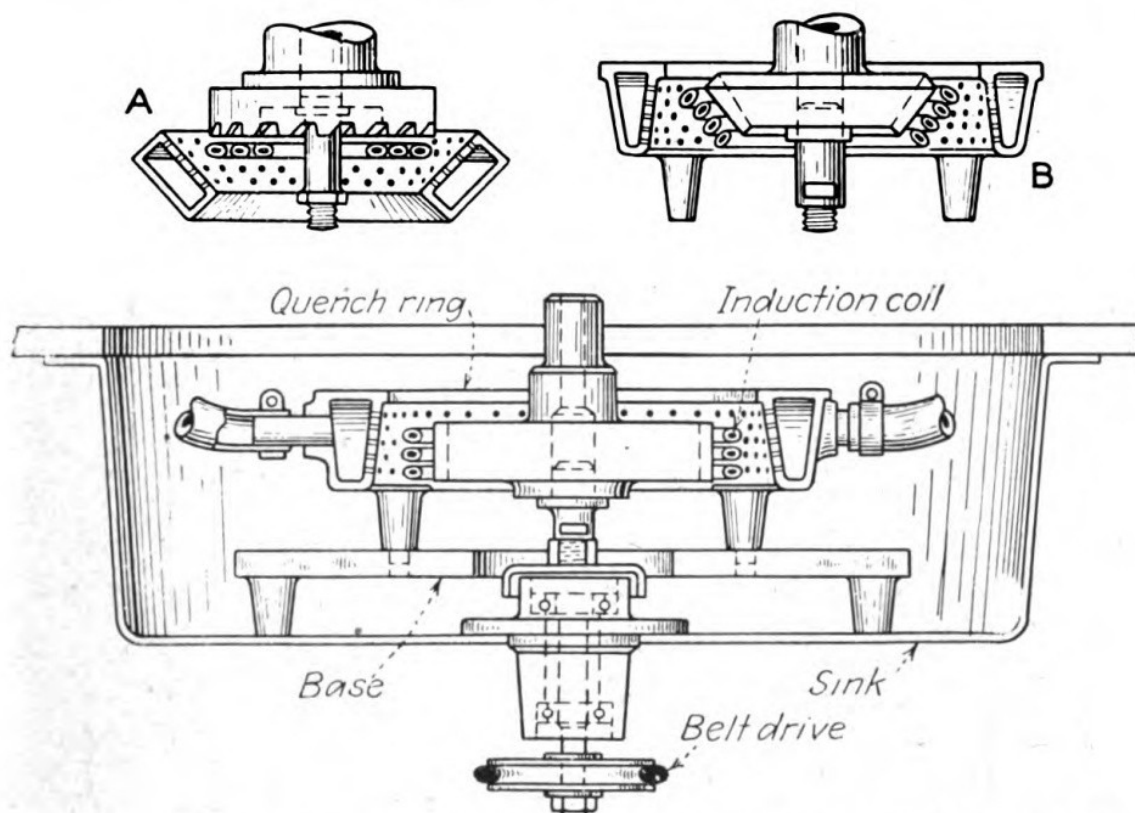

Fig. 151.—Many types of gears can be inductively hardened by means of a multiturn coil and quench ring.

fitted into a spindle. Preferably the spindle should be power driven and rotate during the heating portion of the cycle. Rotation insures a more uniform heat pattern and, naturally, compensates for any variation in the coupling between the work and the induction coil. Usually a speed of 20 to 30 r.p.m. is satisfactory. Hand rotation of the work can be substituted where a convenient method of turning is possible.

A multiturn induction coil surrounds the gear, and around this is located the spray-quench ring. The passage of water for quenching is controlled by a timer, actuating a solenoid-operated valve, normally closed. For this type of quench ring a non-

metallic material is recommended, since a metal ring would set up a magnetic field and absorb heat. A cast phenolic thermo-setting plastic serves well for such an application.

The spacing of the spray holes in the quench ring should be such that a uniform spray is provided. Usually a $\frac{1}{16}$-in. hole, or one slightly smaller, will be found satisfactory. The induction coil should be of the flat type and wound so that the impinging
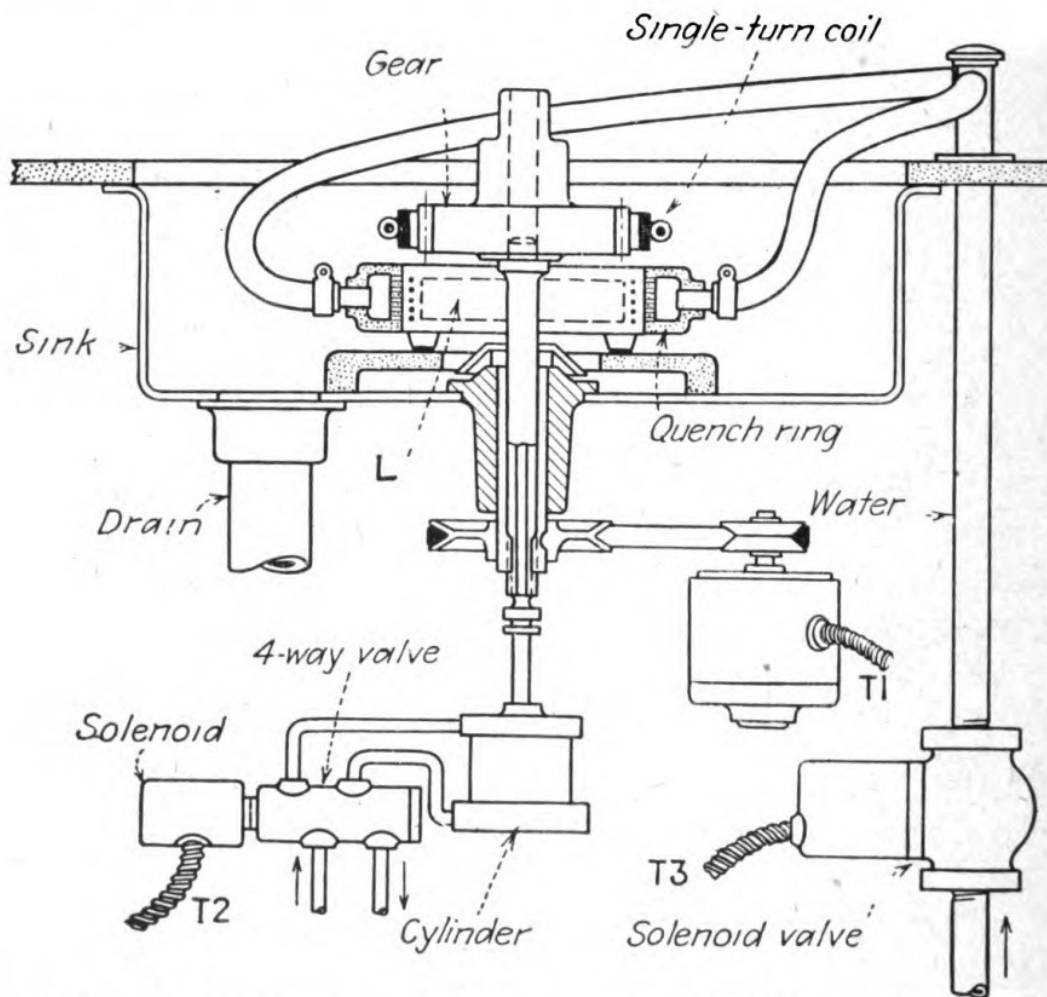

FIG. 152.—A method used for hardening gears in which the work is lowered for quenching after heating has been completed.

spray can pass through it to the heated surface of the work. Other modifications for this type of fixture are shown at *A*, as used for a jaw-tooth clutch, and at *B* for a bevel gear.

Electrically controlled fixtures for gear hardening are often used in induction-heating setups, so that automatically timed cycles can be carried out. An example of this is the method applied to the hardening of gear teeth, as illustrated in Fig. 152. The operation includes heating of the teeth, lowering the gear

to the quenching position, quenching, and returning it to the loading position. These cycles are carried out by a multi-stage timer and the entire operation is automatic except for loading and unloading the gear, which is located on the stud end of a rotary-driven spindle.

With a gear in place, the cycle is started by a push-button station. The high-frequency heating coil is energized and, at the same time, the spindle is rotated at a moderate speed by a slow-speed shaded-pole motor, having connections T_1 to the timer. When heating has been completed the spindle rotation is stopped and the spindle is lowered instantaneously by the air cylinder, actuated by the solenoid connections T_2, so that the
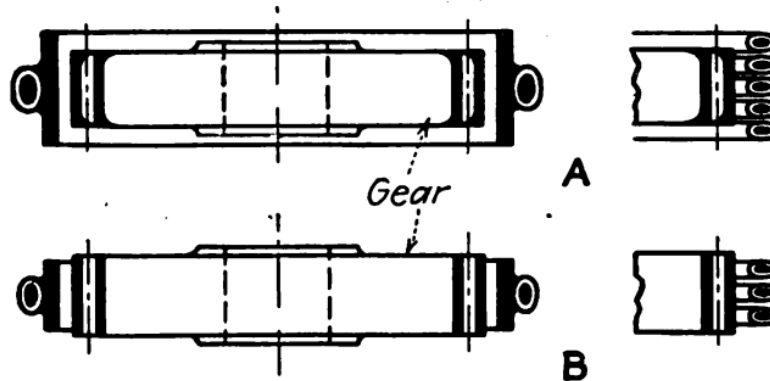
FIG. 153.—In hardening spur gears, it is often advisable to arrange the height of the coil so that it does not exceed the face of the teeth.

gear assumes the position shown at L. At the same time, the water quench is engaged by connections T_3 of the solenoid valve, which normally is closed. After a predetermined spray quench, this valve is closed and the spindle is returned to its upper position, thus completing the cycle. The coil used for heating the gear teeth is of the single-turn type.

In the hardening of gear teeth it is necessary to proportion the height of the heating coil to the surface of the teeth. When the heating coil is of greater height than the face of the teeth, as at A in Fig. 153, there is a tendency for the top and bottom surfaces of the gear blank to absorb heat. On the other hand, with a coil having a height slightly less than the face of the teeth, as shown at B, the heat pattern will be more evenly distributed.

When using a single-turn coil for gear hardening it is possible to make its height at least equal to the face of the teeth; then, after trial, the coil can be trimmed down until the proper heat pattern has been obtained. With multiturn coils, however, it

may become necessary to provide one less turn or, perhaps, to alter the spacings of the coil turns as needed.

When there is a choice between oil-hardening and water-hardening steels, it is better to use the latter, because of more favorable quenching conditions.   With high-frequency induction heating the hardening cycle can be automatically controlled, so that with the use of a fixture and a quench ring a gear can be heated and quenched at one setting.   This is possible also with some types of gears requiring oil quenching, in which case an oil reservoir, pump, oil cooler, and solenoid valve are required. In other cases of oil quenching it is necessary to heat the work and then drop it into an oil bath.

18 or 20 Pitch   12 or 14 Pitch   8 or 10 Pitch   4 Pitch
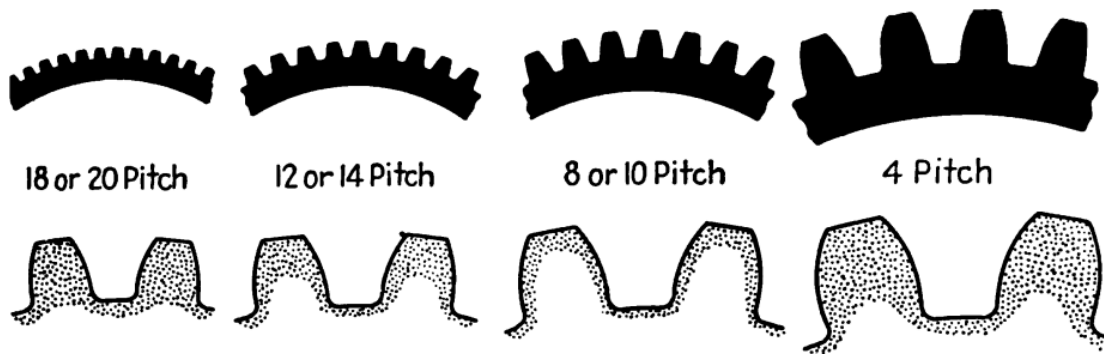
Enlarged section of teeth showing heat penetration

Fig. 154.—Typical heat penetrations of gears having different tooth sizes, when heated by cylindrical coils.

Heat Penetration.   When gears are hardened by high-frequency induction heat at frequencies of 100 to 500 kc., the resultant hardness zone will vary somewhat according to the size of the tooth.   With gears having small teeth, of about 20 pitch, for which a straight cylindrical coil is used, the entire tooth is usually heated, as shown in Fig. 154 at the left.   With a slightly larger tooth, of about 12 pitch, the heat pattern begins to follow the contour of the tooth, as shown in the enlarged view.   On gears having teeth of 8 or 10 pitch, the heat pattern follows the contour of the teeth closely, and a uniform casehardening is obtained.   When the tooth is larger, such as the 4-pitch contour shown at the right, it becomes difficult to "throw" the heat down to the bottom of the tooth, with the result that the upper portion becomes deeply heated and the heat pattern resembles that obtained on finer teeth.

From this it will be seen that teeth of 8 or 10 pitch are best, but that a favorable condition also prevails with those of 12 or 14

pitch. Furthermore, it will be seen that the application of high frequency for the hardening of gear teeth in this range offers a variation in heat patterns and hardness zones. For shallow hardness penetration, for example, the surface only is heated and then quenched, as has been described. For a deeper heated zone additional heating time is provided so that the penetration of eddy currents will be increased, after which the heating cycle
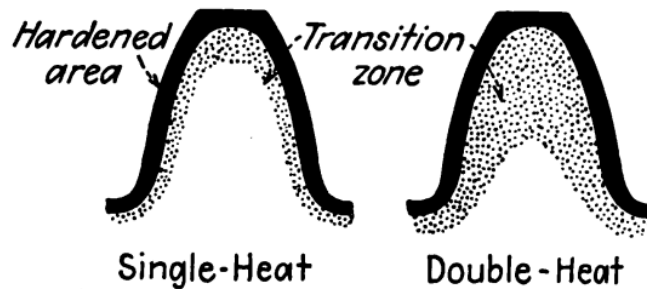

FIG. 155.—Variations in transition zones can be obtained by the application of double heats.

is followed by a quench. If the entire tooth is to be hardened, the heating portion of the cycle is increased that much longer and then followed by a quench.

When gear teeth of 8 to 10 pitch are surface-heated and quenched, the transition zone is shallow, as indicated at the left in Fig. 155. There is no strict line of demarcation, but more of a gradual blending of the hardened area to the core. However, where a deeper transition zone is wanted, this can be accomplished by a double heat. For this the teeth are heated somewhat deeper than merely on the surface, then a delay period is allowed. Following this, the surface is reheated, then quenched so that a transition

FIG. 156.—A formed-type heating coil used for the hardening of a gear having a large tooth form.

zone as shown at the right is obtained. A cycle of this kind can be made fully automatic by the use of a multi-stage timer.

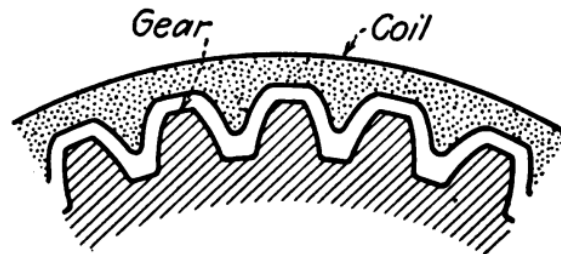Going back to the larger tooth form, such as the 4 pitch referred to, it is possible to use a formed or cast heating coil, as shown in Fig. 156, in which the inner contour conforms approximately to the shape of the gear teeth. This design gives a more uniform distribution of heat around the sides and bottom of the teeth. For exceptionally large gears, however, it is best to heat and

quench each tooth separately, or perhaps in small multiples, depending on their shape, length, and suitability to the power output of the high-frequency generator.

Shaving Teeth before Hardening. An advantage in high-frequency hardening is the possibility of shaving the teeth before hardening. Usually shaving is applied to heat-treated gears having a hardness of 32 to 38 Rockwell C, with no subsequent heat-treatment after shaving. With the induction-hardening method, however, it is possible to shave the gears when soft, and then harden the teeth as a final operation. This procedure has
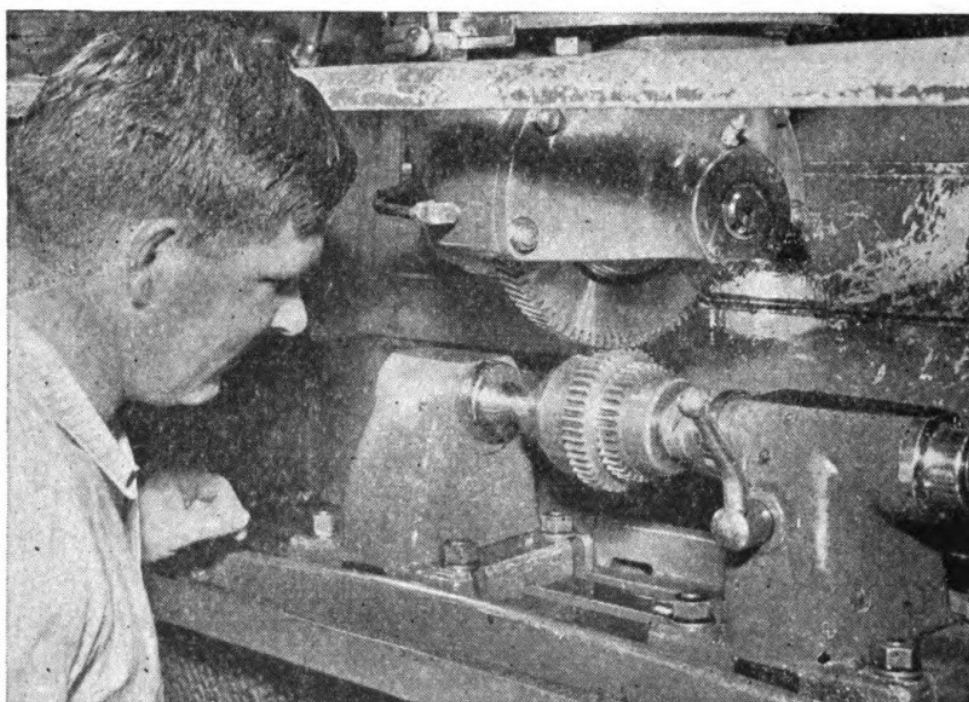
FIG. 157.—Spur gears can be shaved as a final finishing operation, and then inductively hardened.

many advantages, outstanding among which are a harder tooth and less wear on the shaving cutters. In Fig. 157 is illustrated a typical shaving setup for gear teeth of a double-cluster gear, which will be induction hardened on both sets of teeth as the next and final operation. The chart in Fig. 158 shows a typical tape reading of a gear before shaving, after shaving, and after induction hardening. Each horizontal line represents 0.001 in., and a comparison will show that no deformation or runout has resulted from the hardening operation.

Another saving made possible by high-frequency induction hardening is the elimination of cleaning after hardening. Usually a scale is formed when gears are hardened, so that a cleaning

operation is required. With induction hardening, however, practically no scale is formed beyond a discoloration of the surface.
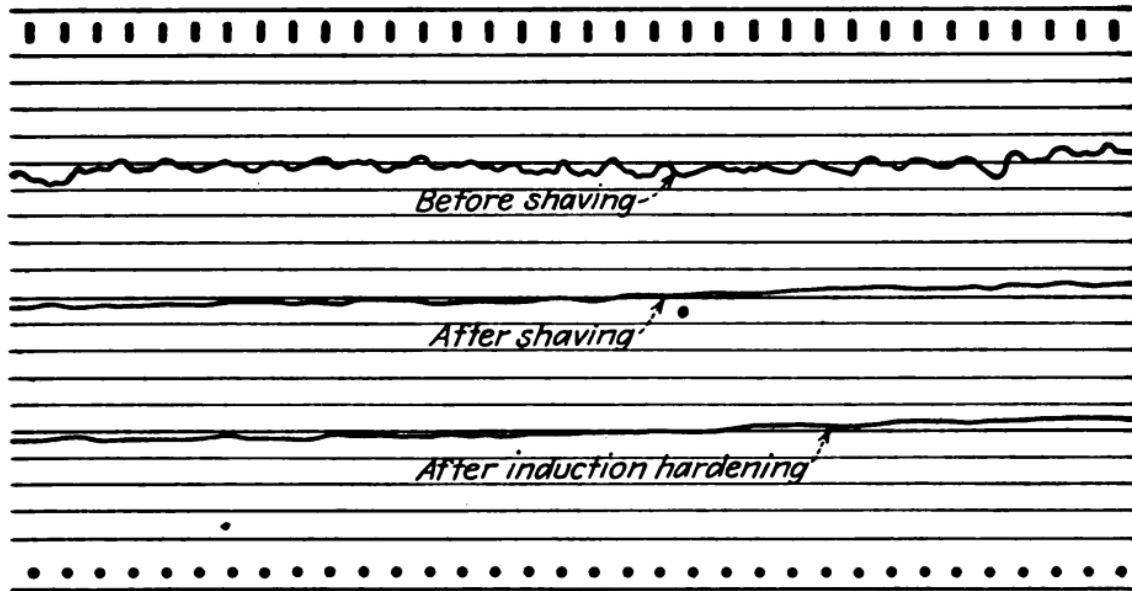

FIG. 158.—Typical tape readings of a solid-type gear, taken before and after induction hardening.

Hardening-time Cycles. As a comparison of the time required for hardening standard types of spur gears by high-frequency induction-heating generators operating at about 200 to 400 kc. and with an output power of about 20 kw., the gear shown at *A* in Fig. 159 can be heated in about 8 sec., and the quench will
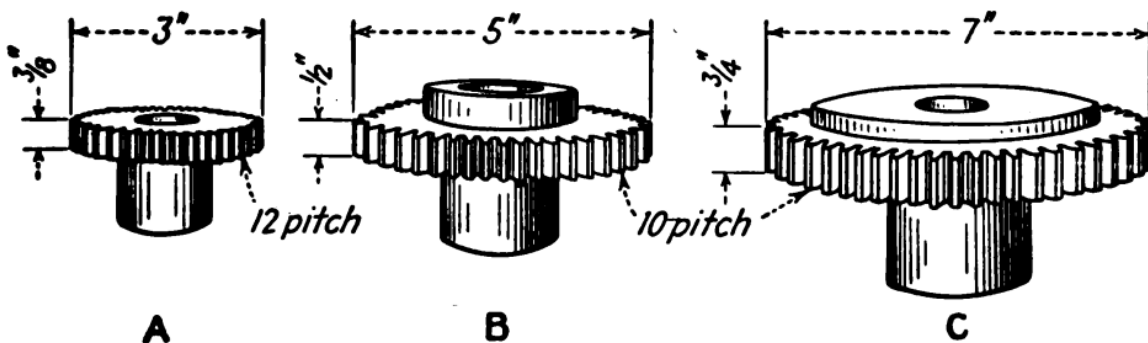
FIG. 159.—Three sizes of spur gears, on which the teeth can be heated in from 8 to 25 sec. Spray quenches of from 5 to 12 sec. are also required.

require 5 sec. The gear at *B* will require a heating cycle of 12 to 14 sec., followed by a quench of about 7 sec. For the gear shown at *C*, the heating time will be 20 to 25 sec., followed by a quench of 10 to 12 sec. All these estimates are based on the use of a 0.40 to 0.50 carbon steel of the water-hardening type, using a closely coupled heating coil.

Another process change which has many advantages is the assembly of bushings and inserts prior to hardening. If a gear is to be provided with a bronze sleeve bushing, this can well be assembled before the teeth are cut. In the hardening operation the heat will not travel so far as the bushing. Formerly it was often necessary to locate the gear from the pitch circle and grind the hole concentric with the pitch diameter, after which the bushing was inserted. An example of a 6-in. diameter gear with a bushing assembled in the hole before the induction-hardening operation is illustrated in Fig. 160. The teeth of this gear
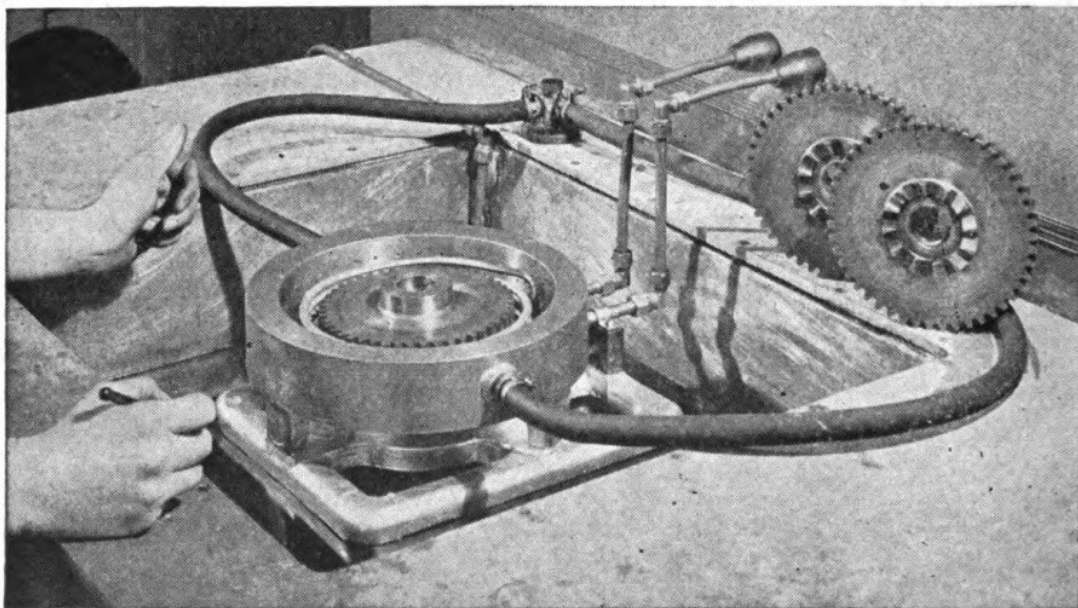
FIG. 160.—Some gears can be hardened after inserts have been assembled. (*Courtesy of Van Norman Co.*)

are cut after the bushing has been assembled, which assures concentricity.

One of the outstanding advantages of high-frequency heating for the hardening of gears is the possibility of heating only the surfaces requiring hardening. Two representative examples are illustrated in Fig. 161. The upper gear is cut integrally with a shaft which, in turn, is mounted on a ball bearing. Since there is no advantage in hardening the entire part, it is possible, with induction heat, to harden the teeth only.

The lower example is a double-cluster gear of the same type, made in one piece. In processing this part each gear is hardened separately, so that two operations are required for hardening. It would be possible to harden both gears simultaneously by making a double-type induction coil, but the problems involved

in spacing the coil with relation to the work, as well as in compensating for the differential in the diameter of the gears, might cause complications.

After all, the hardening operation is handled so rapidly that little time would be gained by trying to combine the two operations. The small gear, which is $2\frac{1}{2}$ in. in diameter, is heated in 7 sec., with a quench of 4 sec., whereas the larger one, which is 4 in. in diameter, is heated in 13 sec. and quenched in 7 sec. From this it will be seen that the total hardening time, aside from loading, is 31 sec. per piece. If both gears were combined in
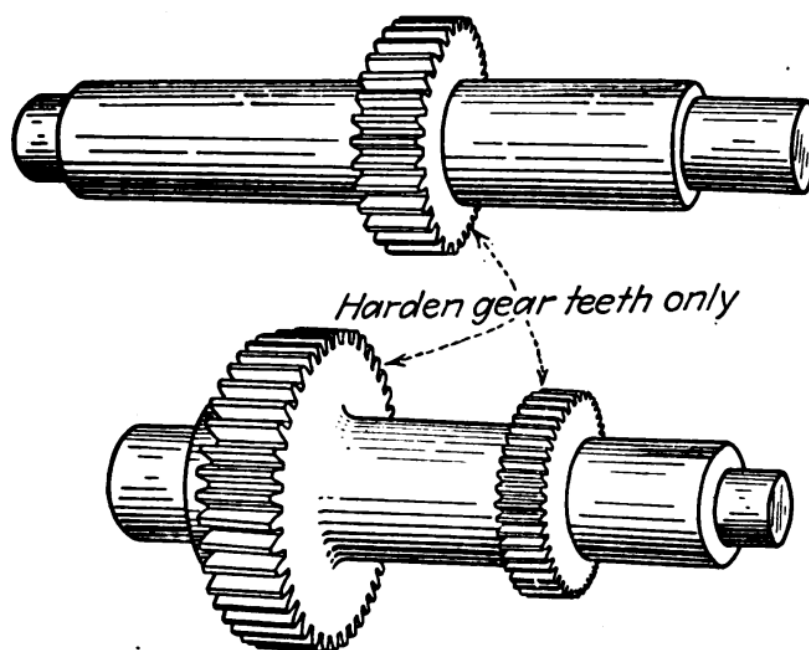
Fig. 161.—Two gears made with integral shafts, on which only the teeth require induction hardening. Practically no deformation results with such gears.

one heating cycle the total time would be about the same, but the results would probably not be so uniform.

A setup for hardening a gear cut integrally with a shaft is illustrated in Fig. 162. The gear is mounted in a horizontal-type fixture between centers, and the induction coil surrounds only the section to be hardened. The fixture includes a base, a quench ring, and multiturn copper-tube induction coil. The gear measures $2\frac{1}{2}$-in. in diameter, and is heated in 10 sec., followed by a 6-sec. quench.

Distortion of Gears. Again, the elimination of straightening is a point in favor of the induction-hardening process for gears of this type. For example, with such a gear as that shown, it is likely that some warpage or deformation would result if the entire

part were heated for the hardening of the teeth only. It would thus be necessary to add a straightening operation, which at times can be quite troublesome.
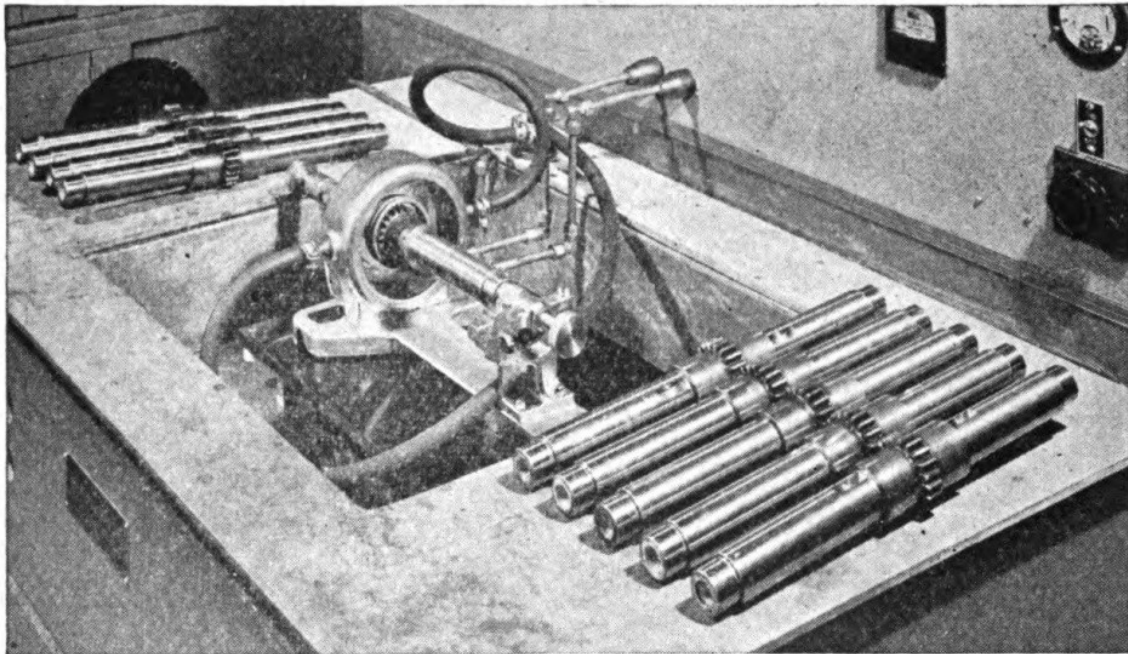

FIG. 162.—Hardening the teeth of a gear cut integrally on a long shaft. No straightening operation is required after hardening. (*Courtesy of Van Norman Co.*)

In hardening gears by high-frequency heat, very little distortion takes place in the average gear. However, there are naturally some designs in which deformation will occur. Refer-
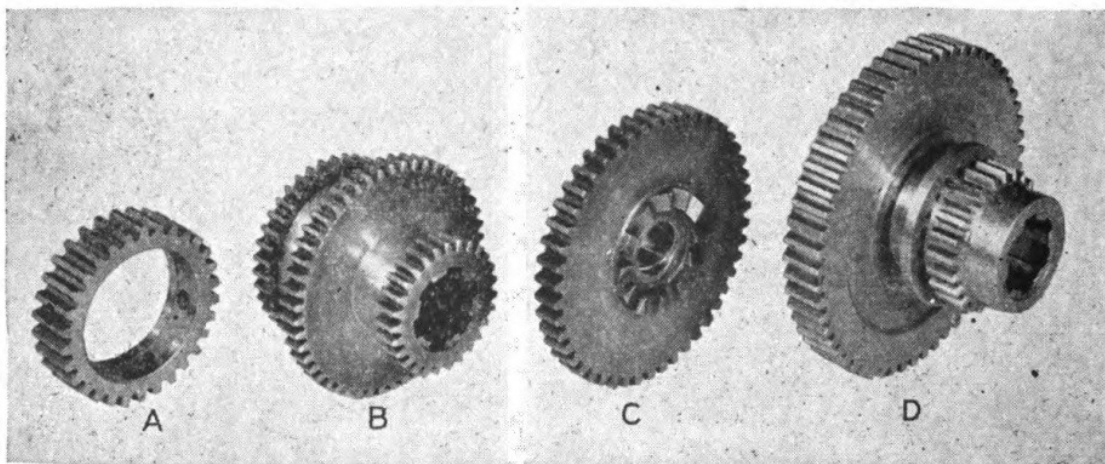

FIG. 163.—Various types of gears which lend themselves to induction hardening of the teeth only.

ring to Fig. 163, the gear at *A* is thin in section and, regardless of the kind of heating applied, there is a likelihood of some distortion; induction heating would be no exception. An advantage

in hardening a gear of this type would be high power and high frequency, so that the surface of the teeth would be heated to quenching temperature before the conduction of heat to the surface directly below could take place. In this way deformation would be greatly minimized.

The gear shown at *C*, however, is solid and, when hardened by high-frequency heat, there will be practically no change in size or shape of the gear. Many tests have been made before and after hardening gears of this type, and at the most there might be a slight increase in size at the pitch diameter; but the concentricity will remain unchanged. Usually, if a gear changes one way or the other, it can be quickly detected after one or two tests, so that proper allowances can be made in machining the teeth.

The example shown at *D* is a double-cluster gear, which has a multi-spline machined in the hole. When the larger gear is hardened there will be no distortion; but when heat is applied to the small gear the splined hole is likely to close in slightly, depending upon the wall thickness between the hole and the outside of the teeth. However, since only the contour of the gear teeth is hardened, the material around the hole will be unaffected as far as hardness is concerned, and it is possible to rebroach the hole with a hand broach to remove any deformation that might have occurred.

The example shown at *B* is a triple cluster with three gears of different diameters, all of which are hardened separately. Here, again, if the amount of material between the hole and the teeth is thin, there is likely to be some closing in of the hole.

By having full knowledge of what is needed to harden gears successfully by the high-frequency-induction process, it is possible to incorporate these requirements in the original design. Generally speaking, induction hardening can be applied to, perhaps, 90 per cent of all gears in the range covered by this method. The few that might give trouble can often be corrected by slight modifications in design, usually in proportioning the amount of steel around the gear so as to prevent deformation.

In Fig. 164 is illustrated a setup for hardening one of the gear sections of the triple-cluster gear. Here the smallest gear is usually hardened first, next the medium sized, and finally the largest. This process is necessary because the location of the

induction coil for the smaller gears is close to the face of the large one, and if it was hardened first a slight amount of heat might be generated in it when the smaller gears were heated, with a slight drawing effect.   By hardening the large gear last, it is obvious that the heat will be confined to the place where it is wanted and will have no effect on the other gears.

Hardening Bevel Gears.   In hardening bevel gears by means of high-frequency heat, the same general procedure as for spur gears is followed.   The induction coil is wound helically to
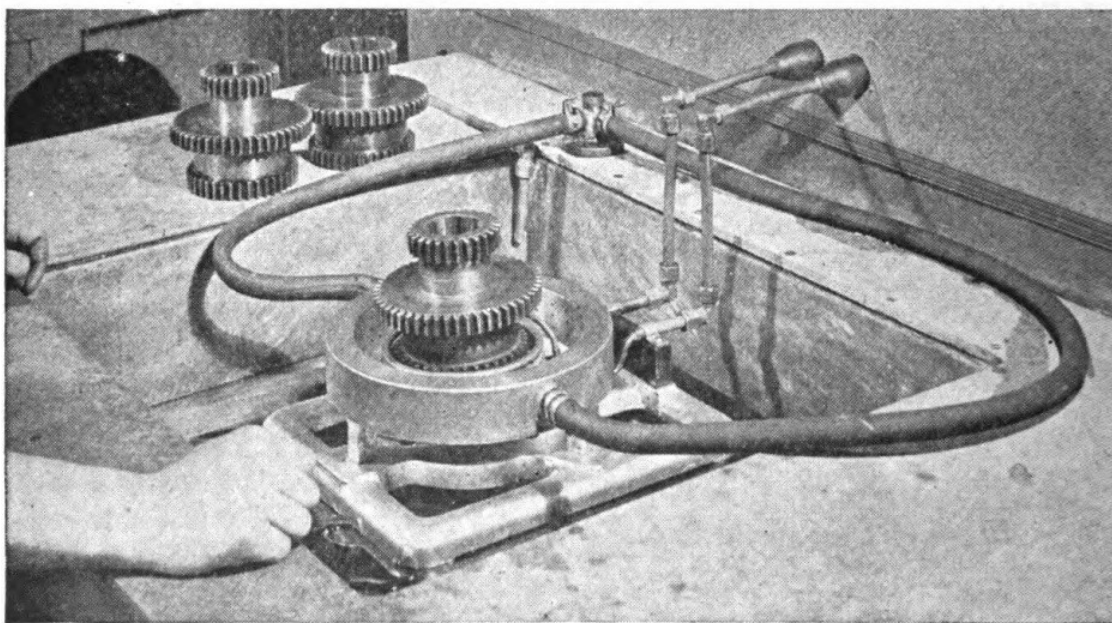
Fig. 164.—A hardening fixture and heating coil used for the treating of a triple-cluster gear.   (*Courtesy of Van Norman Co.*)

conform to the face angle of the gear.   On straight-tooth bevel gears, as shown at the left in Fig. 165, the heat pattern follows the contour of the teeth and uniform surface hardening can be easily obtained.   With spiral-bevel gears, however, because the teeth lie at different angles to their normal flow, the eddy-current lines are disturbed to such an extent that there is a tendency to obtain more heat on one side of the teeth than on the other.

On some sizes of spiral-bevel gears, this can be overcome by applying slightly more heat to ensure hardening of the concave side.   On other forms, however, it is best to carburize the gear after the teeth have been rough cut, then follow with the finish-cutting operation, after which the teeth can be induction hardened by allowing sufficient time to heat the entire tooth.   When the

gear is quenched only the carburized surface will become hardened. While the expense of carburizing adds to the cost of manufacture, it offers the decided advantage of lower heating cost and the absence of scale, as well as the elimination of distortion.
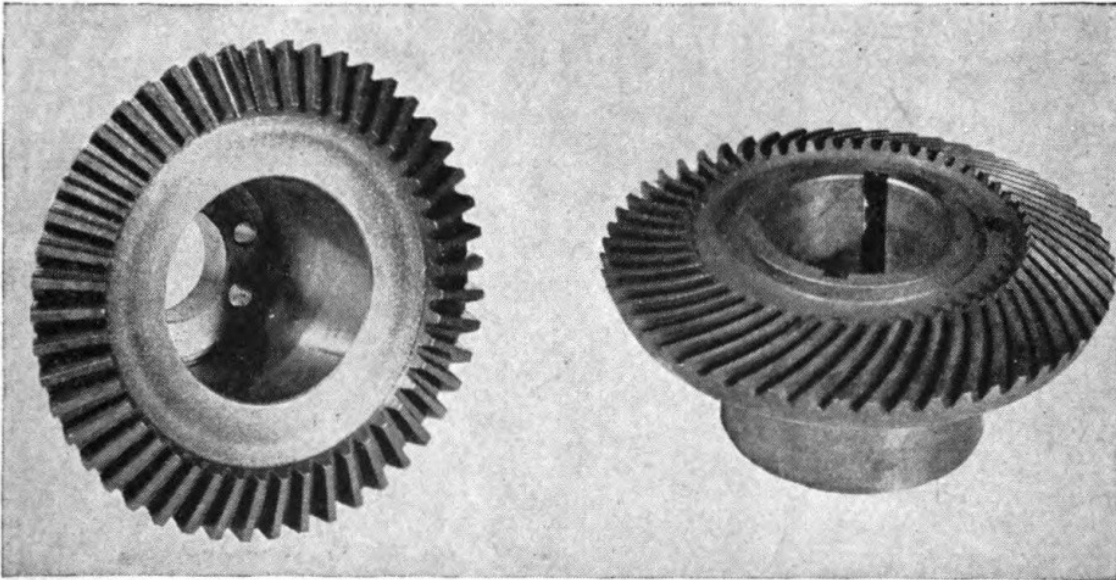

Fig. 165.—Straight-tooth bevel gears can be heated more effectively than those having spiral teeth.

A bevel gear hardened by means of high-frequency induction heating, which might offer some difficulties under usual procedures, is illustrated in Fig. 166. The design includes a hub
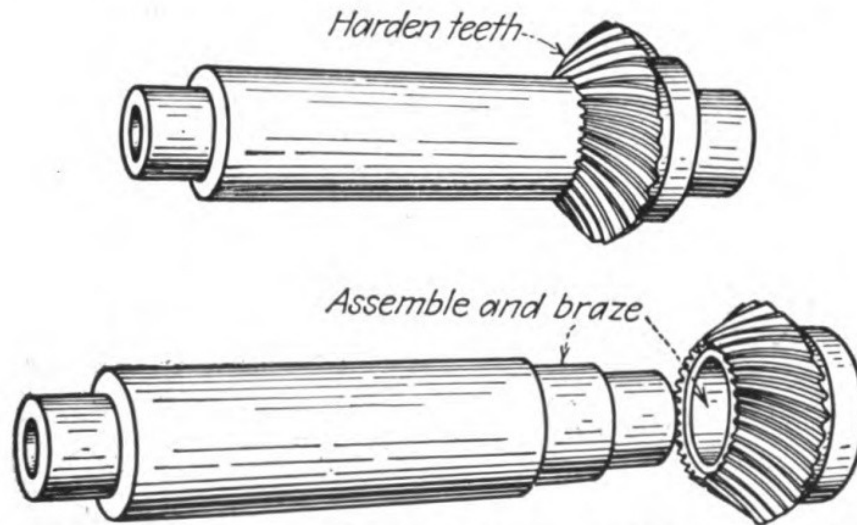
Fig. 166.—A bevel-gear assembly which requires a brazing operation prior to the hardening of the teeth.

that extends in front of the gear face, which naturally had to be assembled after the gear had been cut. If the gear were hardened first and then brazed in place, the heat of brazing would draw the

temper from the teeth.   With high-frequency heating, however, it is possible to braze the shaft into the hub of the gear first, then follow with the hardening operation, localizing heat to the teeth only.   The fixture used for hardening this gear is illustrated in Fig. 167.   The gear is $3\frac{1}{4}$ in. in diameter, and requires a heating time of 12 sec., followed by a quench of 6 sec.

In hardening bevel gears by the high-frequency induction-heating process, the work should be rotated by power or manually, in order to ensure uniform heating.   While it would be possible to construct an induction coil that would heat all portions of the
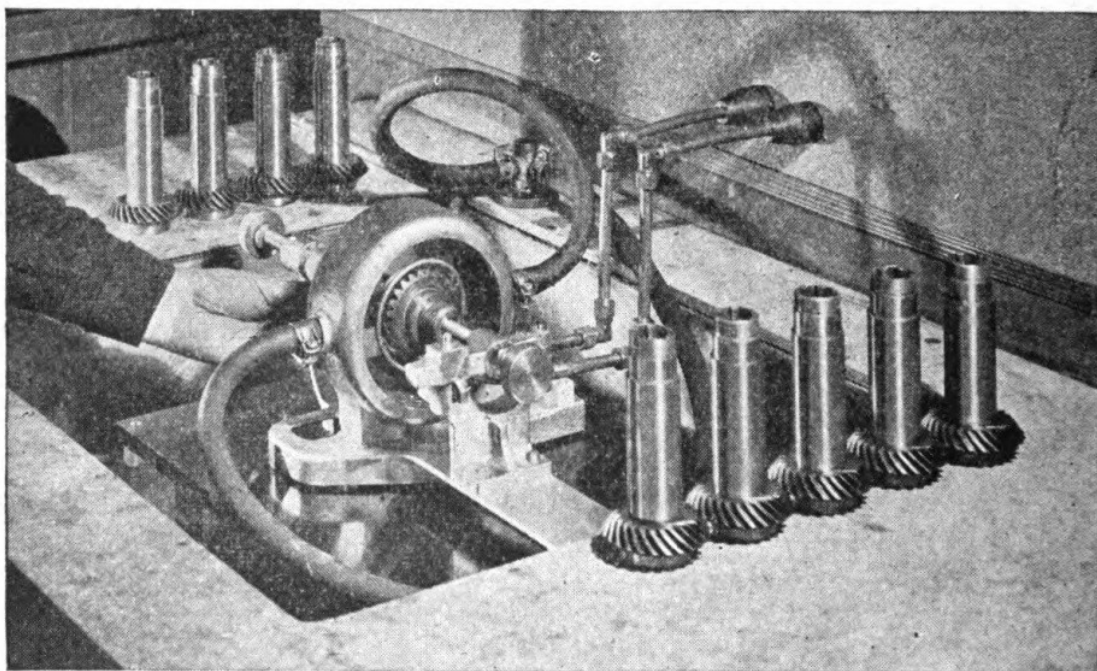
Fig. 167.—Induction-heating setup used for the hardening of bevel-gear teeth. The heating time for this gear is 12 sec.   (*Courtesy of Van Norman Co.*)

gear teeth uniformly, this is not always easy.   Therefore, by turning the work, it is possible to compensate for any slight difference in spacing between the coil and the work.

The current cost for the induction heating of gears is comparatively low.   When a 20-kw.-output generator is used for heating the various types of gears shown, the actual heating portion of the cycle averages only about one-third of the total floor-to-floor time.   The balance is consumed in quenching, removing and loading the work, and changing the fixture from one job to another.   Assuming the power cost to be $0.02 per kilowatt, the operating cost for current would be from $0.25 to $0.30 per hour. The number of pieces that can be processed in an hour depends on

the size of the gears, but the average gear would run through 50 to 60 pieces per hour, so that the average current cost per gear would be less than ½ cent.

In Fig. 168 is shown a representative group of gears suitable to high-frequency induction hardening of the teeth. Various single-, double-, and triple-cluster gears are included. On the large gear in the upper center, as well as on others, may be seen
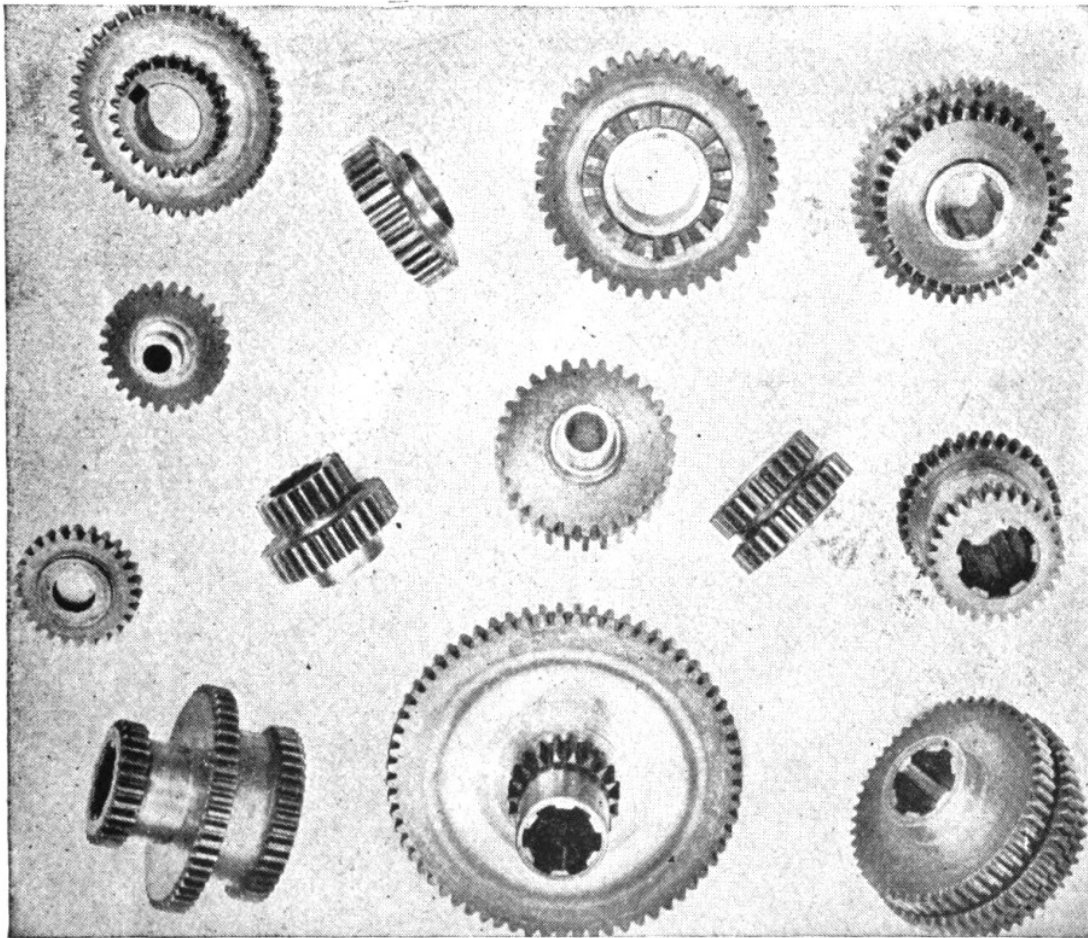

FIG. 168.—A variety of gears which lend themselves to induction hardening, including spur, bevel, and cluster types.

the heat bands set up as a result of high-frequency heating, indicating the depth to which the heat travels. The gear shown at the lower center has three surfaces treated inductively, in three separate operations, namely, the gear teeth, the hole, and the clutch teeth, the respective Rc. readings being 55, 60, and 52.

Hardening Large Gear. In Fig. 169 is illustrated an induction-heating setup for the hardening of a large tractor gear, for which an 800-hp. high-frequency inductor generator is used, and which is illustrated in the chapter describing induction-heating equipment. This gear is made of S.A.E. 1045 steel and is 25.7 in.

pitch diameter, with a 5-in. face.   The gear is preheated to 600°F. before induction hardening of the teeth, and then placed on the fixture, which includes a platform mounted on a vertical spindle. The spindle then is lowered for a distance of about 6 in. so that the gear is brought into proper relation with the surrounding heating coil, which has a coupling of 5/16 in.   The gear is rotated

FIG. 169.—A setup used for the hardening of a tractor gear, approximately 26 in. in diameter, which uses an 800 hp. generator.   (*Courtesy of the Caterpillar Tractor Co.*)

to assure uniform heating and after a 90-sec. heating period, during which time the profile of the teeth reaches a red heat, the current is turned off and a short time allowed for the heat to soak deeper into the case.   During this delay the gear is lowered to the quenching position and then quenched as illustrated in Fig. 170.

The final treatment of the gear comprises a tempering at 300°F. for approximately 1 hr., which produces a surface hardness of approximately 58 to 60 Rockwell C on the surface to lower readings, as illustrated in Fig. 171.

Prior to induction hardening, the gear formerly was made of an alloy-steel billet, which was hardened and tempered to 40 Rock-
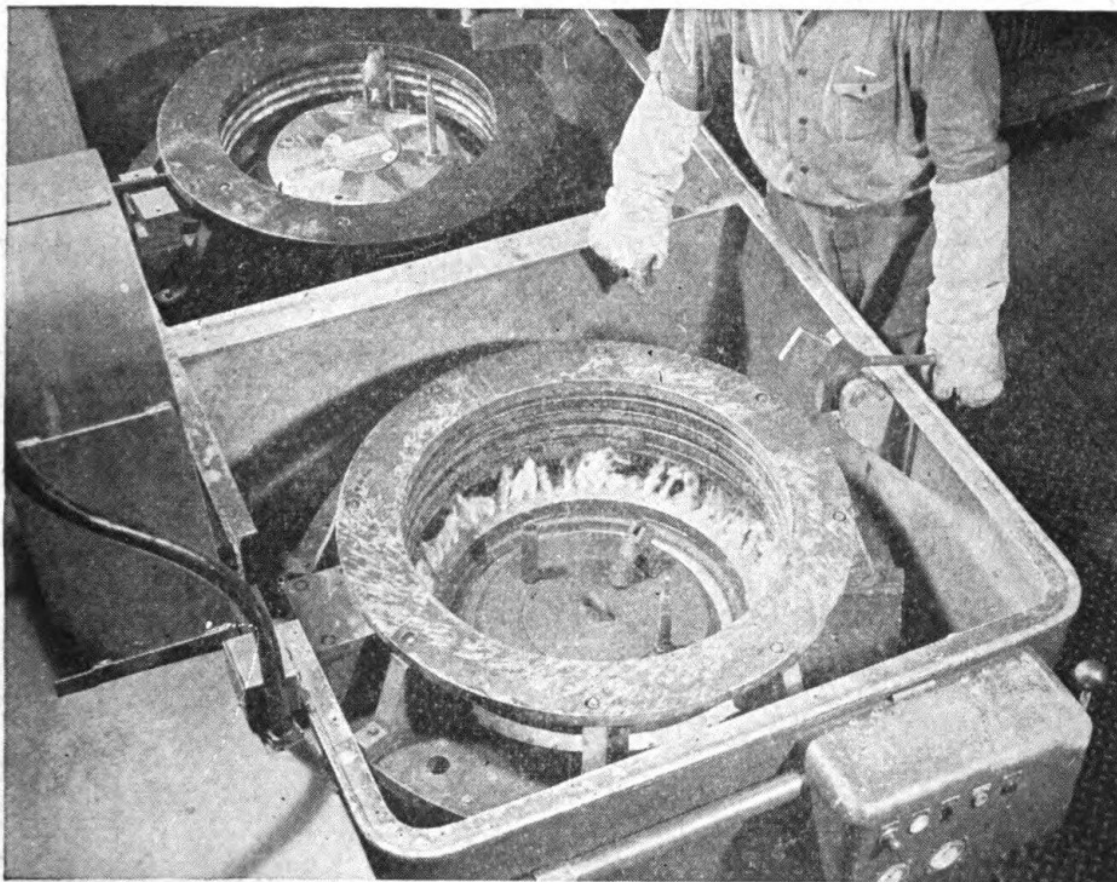

FIG. 170.—After this gear is heated by the coil shown in the upper position, it is lowered to the quenching position, where a spray bath is employed. (*Courtesy of the Caterpillar Tractor Co.*)

well C, after which the machining and cutting of the teeth were carried out. From a production standpoint, the machining was comparatively slow and the cutter cost somewhat high. With the inductive method, however, machining and cutting of the teeth are carried out with the plain carbon steel when soft, which is more practical from a machinability standpoint. Thus cutter life has been greatly increased and production costs reduced. There also is a considerable saving in alloy material, running into several pounds per gear.

FIG. 171.—Cross-sectional area of a tooth of the gear illustrated in Fig. 169, showing the gradient of hardness obtained.

Another application for induction heating is in the standard end-quench hardenability test, referred to as the Jominy test.

With a simple fixture this test can be carried out quickly by the inductive method. It consists of preparing a normalized bar 1 in. in diameter, and 3⅞ in. long, with a ⅛-in.-thick flange, as shown at the right in Fig. 172. The test piece is machined all over, then inserted in the heating coil, being suspended from the flange. The bar is heated with a minimum formation of scale to the proper temperature, then quenched from the end by water flowing through a pipe having a ½-in. orifice, ½ in. from the end of the specimen, and with sufficient pressure to rise to a height of 2½ in. when the test piece is not in place.
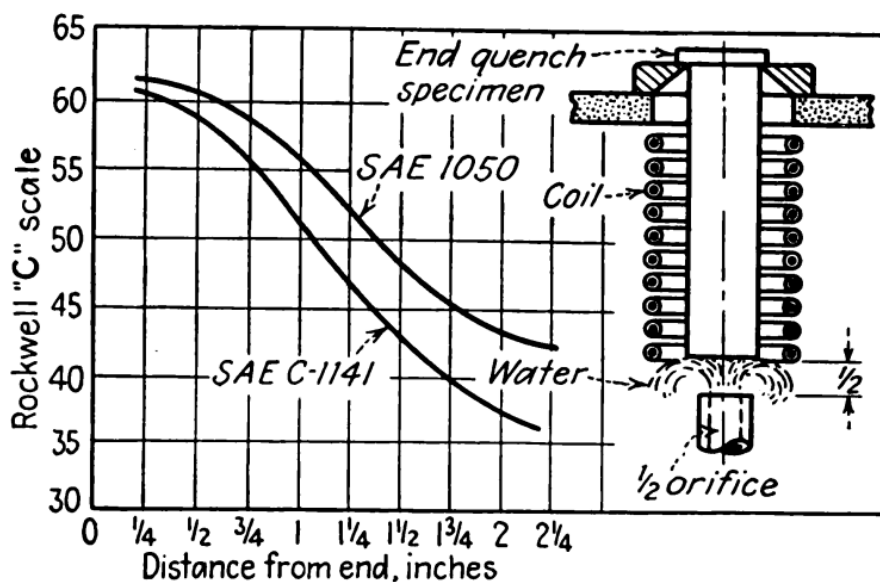
Fig. 172.—Induction heating can be used in conjunction with the end-quench Jominy test used for determining the hardenability of various types of steel.

Water is allowed to flow until the sample is practically cold. Flat surfaces are ground on each side to a depth of 0.015 in., after which Rockwell hardness readings are taken at intervals of ¹⁄₁₆ in. apart.

The rate of quench is very fast on the end of the specimen. Inasmuch as the heat must pass through the sample by conduction, the upper portion of the piece is quenched slowly. This indicates that quenching has been carried out at different rates, which, in turn, will vary the Rockwell readings. This method of testing makes it possible to predict how various steels will respond to heat treatment.

In the chart are shown hardness curves for two representative steels which have been subjected to the Jominy end quench by means of induction heating. The cooling rate of these pieces

varies from 200 or 300°F. per second at the end, to 4 or 5°F. at the top. From this method of testing it is possible to chart the hardness gradient of any section merely by plotting the hardness obtained.

When heating and quenching of a surface are required, it is sometimes possible to use a tubular coil provided with spray holes, and to limit the flow of water to the quenching portion of the cycle. Usually this type of coil is applied only when the heating time is short, since overheating might result. A quenching coil of the built-up type, made with cooling tubes, is illus-
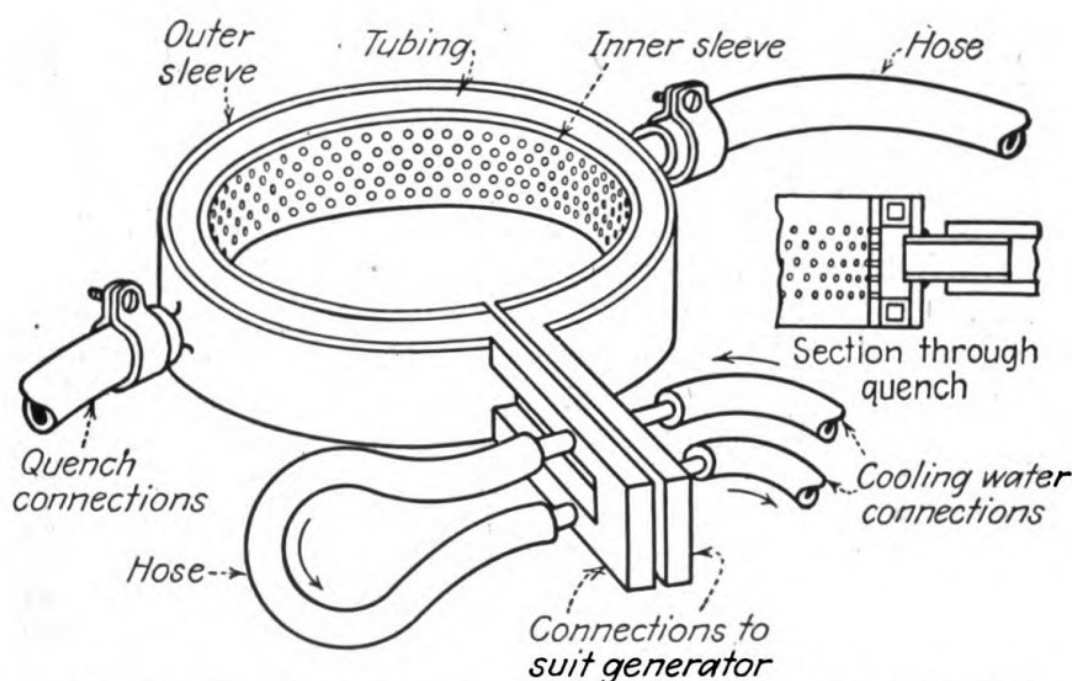
FIG. 173.—A built-up heating coil for parts such as gears, which is provided with integral cooling tubes.

trated in Fig. 173. This coil has two tubes for cooling, located between an outer and an inner sleeve, all brazed together, as shown in the cross-sectional view taken through one of the water-quench connections. The cooling water is fed through a separate outlet and circulates around both cooling tubes, built into the coil assembly. The arrangement of the cooling-tube connections and the two leads to the generator can be modified as needed to suit the high-frequency outlet terminals. The inner sleeve is made with a series of holes through its center portion, which usually provides sufficient quench for a surface as wide as the coil is high, since the water is well distributed in both directions from the center when it strikes the surface of the work.

Even though the application of induction heating to high-speed steel is somewhat limited—usually to small tools with thinner sections—it is quite possible that developments will take place in both metallurgy and inductive heating, so that its field will be widened.
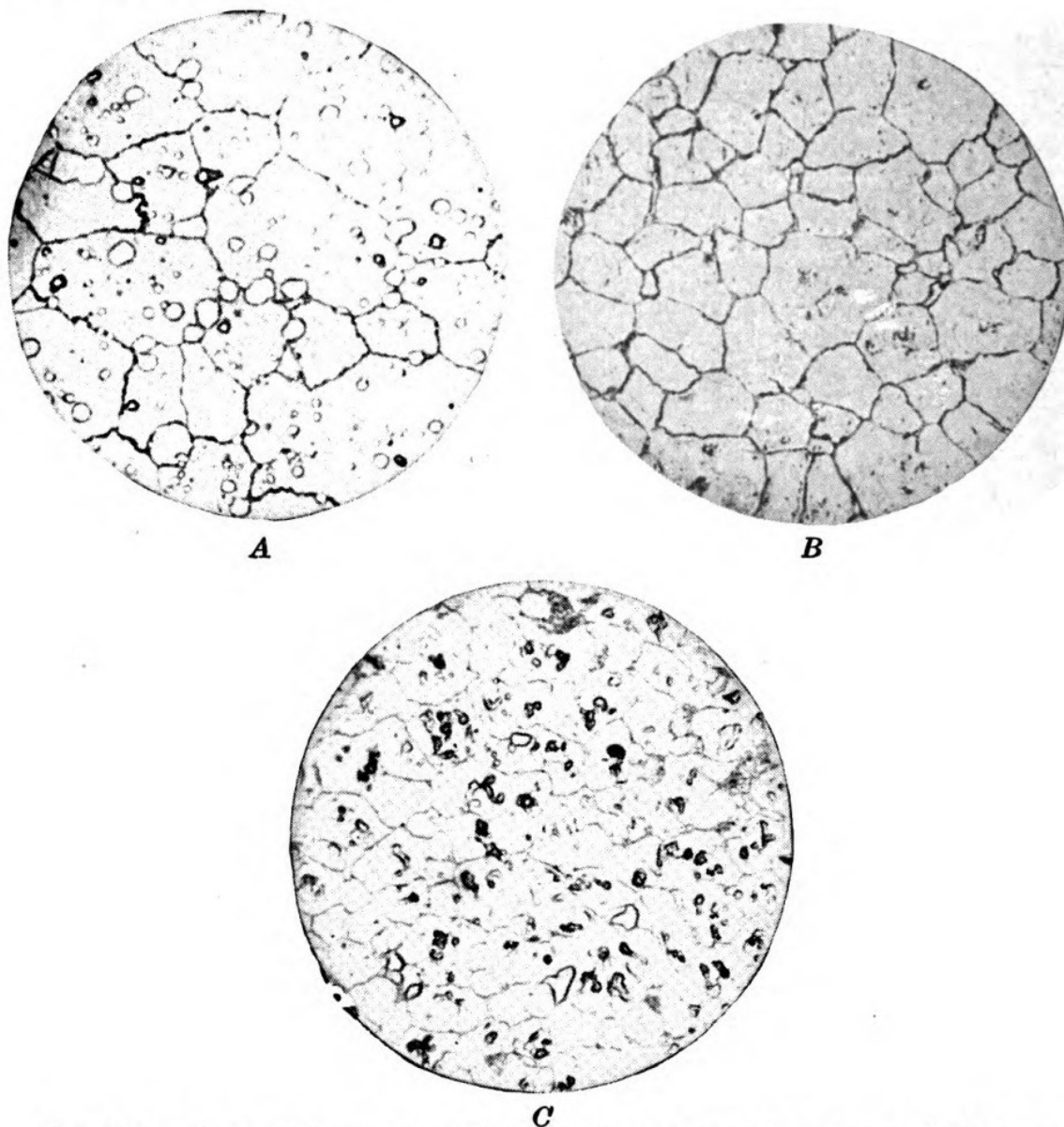

FIG. 174.—Microphotographs of inductively hardened high-speed steel, showing the result of heat in relation to carbide solution. (*Courtesy of Richard F. Harvey.*)

Some tests conducted with high-speed steel hardening have shown favorable results. The microstructure of conventionally hardened high-speed steel consists of undissolved alloy carbides, distributed in an austenitic-martensitic matrix, as illustrated at the left in Fig. 174 at *A*. The grains have a definite size, depending on the hardening temperature employed and the actual time

at the hardening temperature. The grain size and degree of carbide solution materially affect the toughness, red hardness, wear resistance, and cutting characteristics of high-speed steel.

In general, better cutting qualities are obtained with increased grain size and increased solution of the carbides; but since the toughness is adversely affected by increasing the grain size it is often necessary to compromise to some intermediate grain size for most cutting applications. In conventionally hardened high-speed steel, there is about 7 per cent of undissolved alloy carbides

The microstructure of induction-heated high-speed steel, rapidly heated for hardening, is shown at the right of the illustration at *B*. It will be noted that the grain size is smaller and the degree of carbide solution considerably greater than that usually obtained in high-speed steel hardened in the regular manner. High-speed steel rapidly heated by induction is highly austenitic and multiple tempering should be employed to convert this constituent to hard martensite most effectively. At the bottom at *C* is represented the microstructure of underheated high-speed steel. It will be noted that the time of heating is somewhat less than is necessary to dissolve substantially all of the carbides, as illustrated in the structure at *D*.

The cutting performance of induction-hardened high-speed tools has often been found excellent and it is expected that induction heating will be more widely used in the future to treat all types of tool steel.

Hardening Crankshafts. One noteworthy application for induction hardening is the treating of connecting-rod and main bearings of crankshafts, as illustrated in Fig. 175. The method used up to the advent of induction hardening required the heating and quenching of the entire crankshaft, followed by a drawing operation. Also alloy steel was used. Now it is necessary only to harden the actual surfaces which are subjected to wear and, at the same time, use a simplified form of carbon steel, such as S.A.E. 1050. In the operation shown, which is of the vertical type, three or four bearing surfaces are hardened progressively. The crankshaft then is processed through another induction-hardening machine arranged to harden additional bearings. Usually about three machines are required to handle all the surfaces requiring treatment. Since all the units are controlled and timed automatically, it is possible for one operator to service

them consecutively and thus obtain a relatively **high rate of** production. This method of hardening is carried out on large Diesel engine crankshafts, in which case the parts require mechanical equipment, usually in the form of a conveyor line, so arranged that one bearing is hardened at each station. On
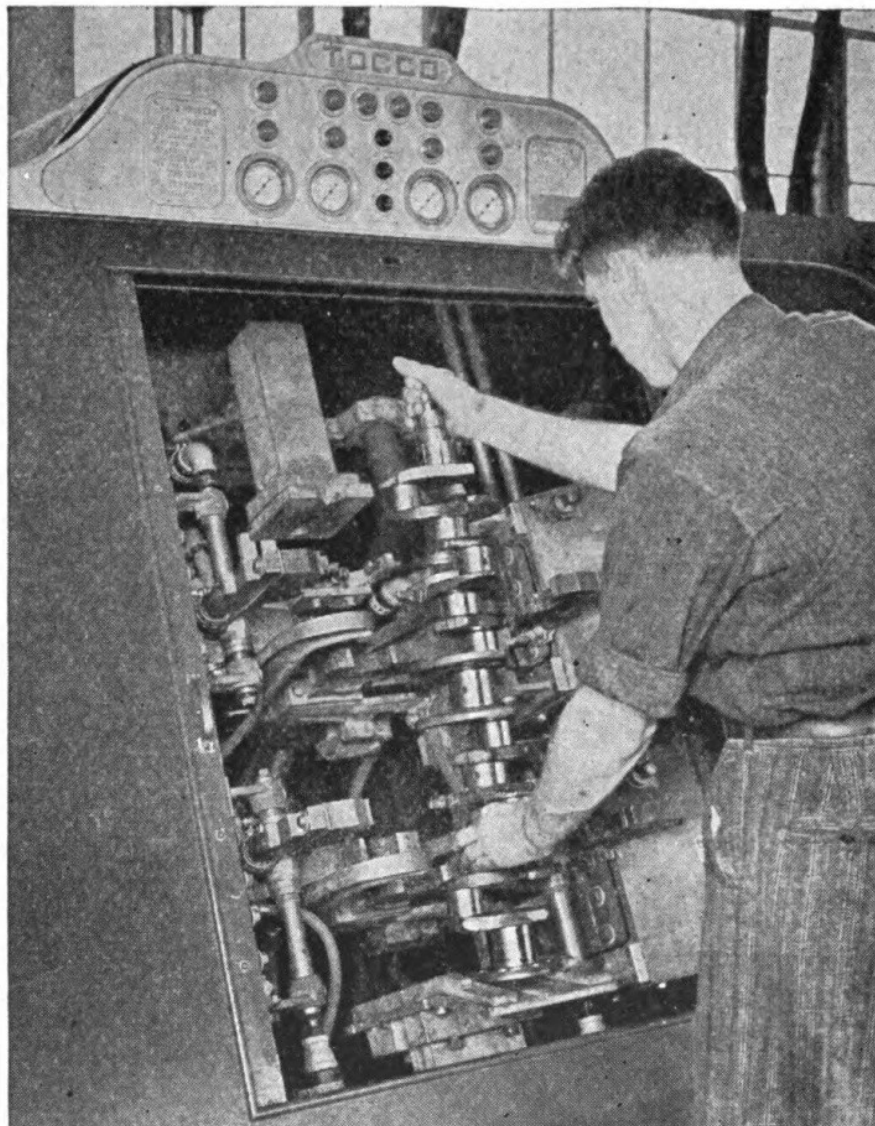

Fig. 175.—A well arranged heating unit used for the hardening of **crankshaft** bearings by means of a motor-generator set. (*Courtesy of The Ohio Crankshaft Co.*)

crankshafts of the kind shown, the surfaces are hardened to 60 Rockwell C, leaving the core tough and ductile.

In hardening such parts as crankshafts, it is necessary to use a split-type or hinged inductor, made of two pieces, as illustrated in Fig. 176. In this setup, a small two-throw crankshaft is shown in the fixture. The part is located from two surfaces into V blocks and is radially aligned by the crank bearing, which is

not being hardened. When the work is in position, the upper half of the inductor block is swung down, then the hinged clamp is brought into place, so that both halves of the inductor can be firmly contacted. The inductor block in this case is made with integral quenching holes, as may be seen.

Air Hardening. In some cases it is possible to surface-harden certain types of parts without the usual quench, because of the steep temperature gradient set up by rapid heating of the surface,
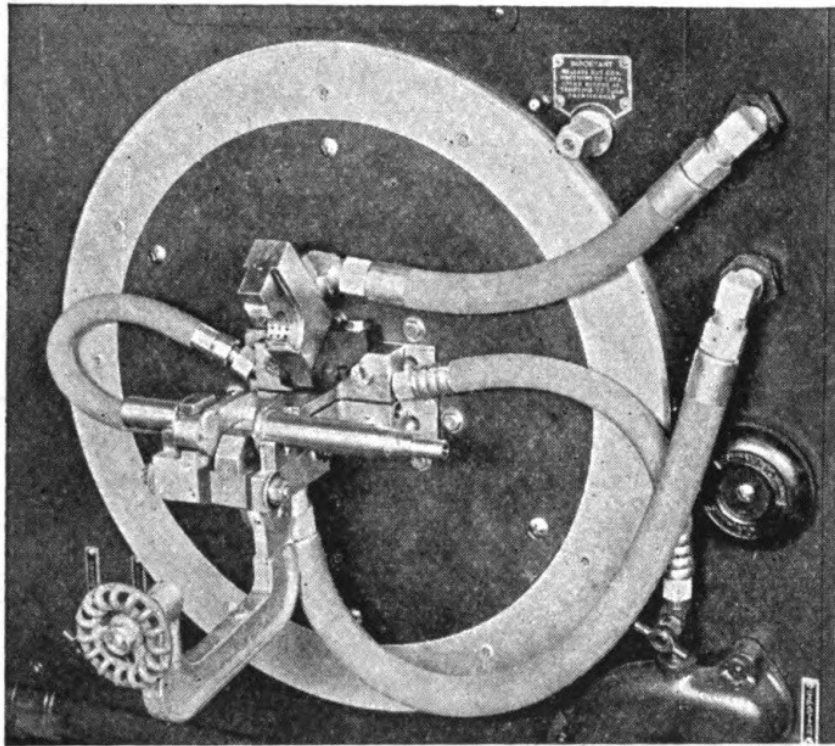

Fig. 176.—An efficient hinged-type inductor used for hardening bearings of small crankshafts. The work is supported by means of V blocks. (*Courtesy of The Ohio Crankshaft Co.*)

followed by rapid cooling. By heating a thin layer of the surface only, in a matter of, say, 2 or 3 sec., and then turning off the current, the surface heat dissipates into the cold mass underneath fast enough to create a so-called "quenching" action. While this process is limited and requires carefully selected frequencies and power supply in relation to the size of the part being treated, it provides a means of localized hardening with some possibilities.

Linked with this method, however, is the necessity of obtaining a steel with air-hardening properties, or with characteristics that offer hardness when quickly cooled. There are limitations to the degree of hardness obtainable and, likewise, control is not as

accurate as with the spray-quenching method used for carbon steels. The power required for this type of heating may run high, especially where high frequencies, on the order of 1 megacycle or more, may be needed.

Oil Spray Quenching. In spray-quenching metal parts, it is possible to use a light oil instead of water when the metal or the steel so requires, and in Fig. 177 is shown a self-contained oil system for this purpose. An oil tank of sufficient capacity is located adjacent to the operating table, as shown. The oil is fed through the circuit by a pump, which normally circulates the oil through a 3-way valve and back into the tank. This valve is
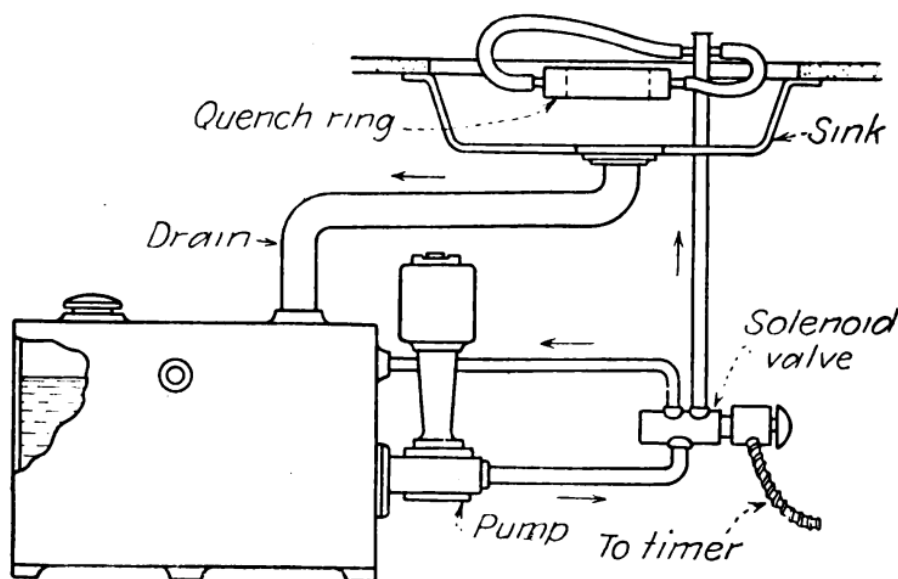
FIG. 177.—Oil-spray quenching can be used for small- and medium-sized parts. A self-contained oil system can be used for this purpose.

solenoid operated, and when switched over to the spray position the oil passes through the quench ring onto the work, and finally back through the drain to the tank. When the solenoid valve returns to its normal position, the spray quench is cut off and the oil circulates through the original course.

Oil quenching is usually limited to parts not subjected to excessive heat, and where the volume of heated mass is not too great. For bigger pieces a submerged quench is to be preferred. The thing to watch is flashing of the oil. Normally with smaller pieces the inductively heated area loses its heat so quickly that flashing does not take place. With a large mass heated to quench temperature, however, flashing might exist.

As a rule an oil-spray installation of this kind will require some means of cooling the oil. A small compressor-refrigeration unit

usually will meet this need. Temperature control should be provided so that operation of the compressor will be automatic and thus maintain the temperature of the oil within a desired range. Or water-cooling tubes may be placed in the oil tank, which also can be arranged with thermostatic control through a solenoid valve. The compressor unit usually is preferred, since it offers better temperature control. Such units are available complete with automatic controls and can be installed directly on the oil tank.

Inasmuch as high-frequency current can be made to operate in a submerged oil bath, it is often possible to carry out hardening
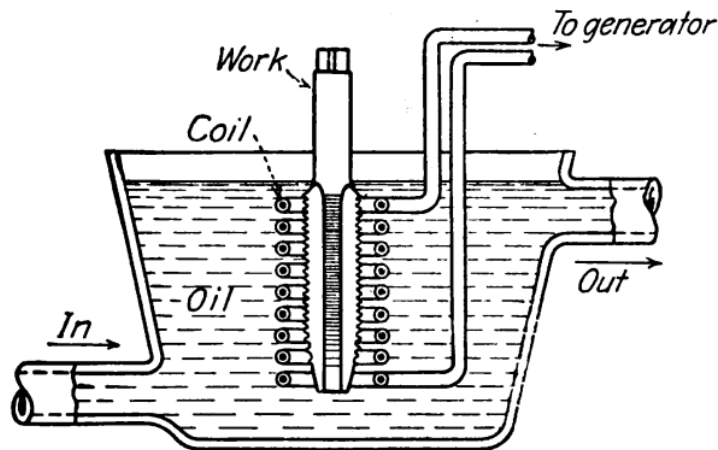
Fig. 178.—Small parts requiring surface hardening can be heated while submerged in an oil bath.

operations advantageously by heating in oil. This principle is illustrated in Fig. 178. Inasmuch as the part is not subjected to the atmosphere, there is less likelihood of scaling, although the oil must be circulated to prevent its becoming overheated.

This type of operation, however, is limited to small pieces and should not be applied for general hardening setups, for which other methods are more effective. In hardening a tool such as a tap or small reamer, however, this submerged-heating process has certain advantages. For work of this kind heat is restricted to the teeth, which heat rapidly, and as soon as the current is shut off the part is quenched automatically. Several grades of light quenching oil are suitable for submerged heating, but, as previously mentioned, only small pieces which can be heated exceptionally fast should be considered.

Semiautomatic Fixtures. An unusual type of hardening operation, using a 50-kw. 9,600-cycle generator, is illustrated in

Fig. 179.   The part is a large sprocket, 24 in. in diameter, having 36 teeth, which are mounted in pairs into a fixture as shown. The sprockets are ¾ in. thick and the teeth are 3 to 4 in. deep and made of S.A.E. 1045 steel.   Four pairs of teeth are hardened simultaneously in a total time of 20 sec., which includes 10 sec. for heating, 4 sec. for quenching, and 6 sec. for indexing.   Four complete sprockets are hardened in 6 min.
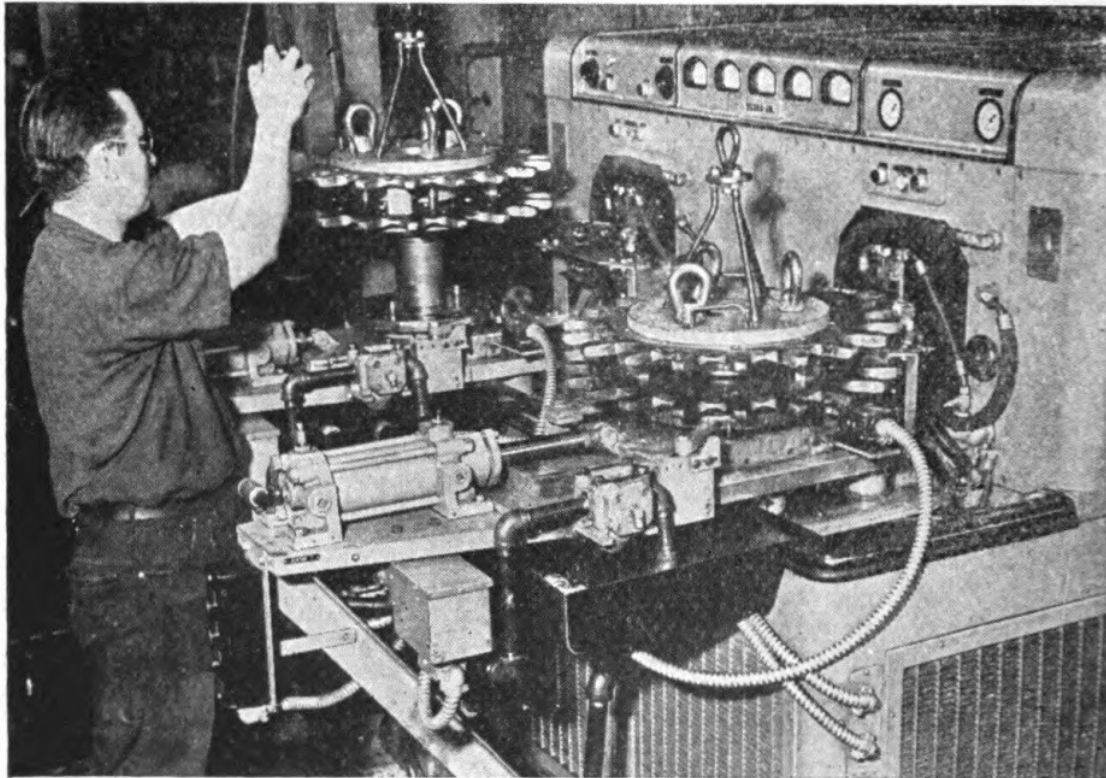

FIG. 179.—An indexing-type fixture used in the hardening of large sprocket teeth. The heating and quenching cycle, as well as indexing, is controlled automatically.   (*Courtesy of The Ohio Crankshaft Co.*)

After the parts are loaded, the operation is entirely automatic. A hydraulically operated cylinder advances the fixture so that the teeth to be hardened enter the induction coil.   Upon completion of a hardening cycle, the fixture automatically returns, then indexes, and finally advances again for the next heating cycle.   This example of induction hardening is representative of the possibilities offered by efficient tooling methods, which often are the major consideration in this class of work.

Another type of semiautomatic fixture which is good for through heating of small symmetrical parts is illustrated in Fig. 180.   The fixture is shown with the front panel removed, so that the induction coils and operating mechanism may be seen.

The parts to be induction heated in this case are small pro-
jectiles, although a variety of other parts can be similarly handled.
The pieces are placed in the magazines and pass through to the
heating inductors, which are multiturn copper-tube coils con-
nected in series. A cam-actuated plate *A* holds the parts in
correct heating position for the predetermined heating cycle,
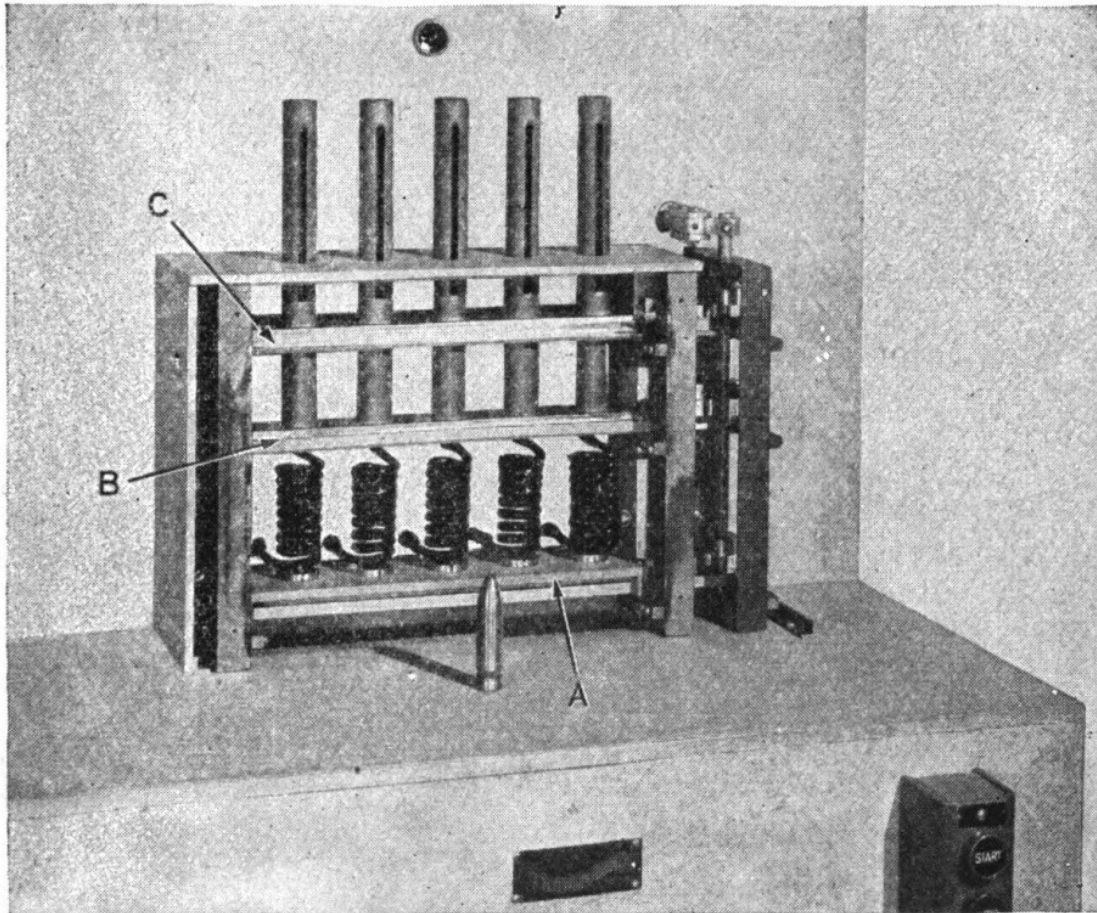after which the plate is withdrawn sufficiently to permit the

FIG. 180.—A progressive-type heating fixture, arranged with automatic
control, used for the through-hardening of small projectiles. (*Courtesy of
Induction Heating Corp.*)

five heated pieces to fall through into the quench tank located
underneath. The plate then returns to the holding position,
when the feeding plate *B*, also cam-actuated and located directly
above the coils, is withdrawn sufficiently to permit five more
pieces to drop into the heating position. A third cam-actuated
plate *C* also is used to control the passage of the workpieces to
the intermediate location prior to entering the heating zone.

Many modifications of this type of heating fixture can be
provided and in some cases, the shape of the part permitting,

only a single cam-operated trip may be required. In any event, a study of the part in question should be made to determine the best method of handling.

Advantages of Induction Hardening. Induction-heating methods applied to the hardening of steel parts offer many advantages. Naturally, much depends on the shape of the part and the type of hardening being carried out. In general, however, the following summary will apply broadly to this method, and will show some of the possible considerations for the hardening of parts where induction heat can be applied:

A low operating cost is made possible as a result of localized heating, especially when compared to parts that have to be heated throughout by other treatments.

A substantial reduction in heating time for a given surface, with the result that an increased output is possible over other methods.

Uniform results after a time cycle has been established, so that rejections are reduced to a minimum, or entirely eliminated.

The possible elimination of subsequent operations, and often the reduction of preceding operations. Cleaning and straightening often are unnecessary.

The use of higher carbon steels for casehardening instead of low-carbon steels that require carburizing.

Substitution of plain carbon steels for alloy steels has great possibilities and will have an effect on material costs.

Depth of hardness can be minutely controlled.

Rapid heating and quenching of the surface causes the inner surface to remain relatively cool and metallurgically undisturbed.

Since induction heat is applied to the work's surface exceptionally fast, there usually is no time for oxidation to take place and only a slight discoloration of the surface results.

Normalizing and tempering operations for induction-heated parts are often eliminated, especially where a spray quench is used.

Because carbon is brought into solution at an exceptionally fast rate, the hardenability of many steels is increased.

The rapid heating and quenching made possible by the inductive method results in a finer grain structure than that ordinarily obtained by other methods.

Induction-heating process permits machining operations to be carried out on surfaces adjacent to those hardened after hardening has been completed.

Skilled operators will not be required in many cases, especially where automatic control of heating and quenching is used, resulting in precision repetition of hardened areas.

Detection of defective parts usually is facilitated by uneven heat patterns, which are prominent around cracks and other defects, simplifying inspection requirements.

A gradient transition zone from the hard surface to the ductile core is obtained so that fracture or breaking out of the hardened area cannot occur, even as a result of deflection.

An induction-hardened surface can usually be finished with a higher degree of smoothness by grinding or boring, as a result of the improved surface-grain structure.

Induction-heating equipment can be installed with other machinery in line production, since its operation is cleaner than other heat-treating units.

Cleaner operation conditions exist with induction-heating installations.

Different degrees of hardness can be obtained within a single workpiece, which sometimes is difficult or impossible by other methods.

Induction hardening opens up new possibilities in product design.

CHAPTER VI

FIXTURES FOR INDUCTION HEATING

Fixtures for high-frequency induction heating can be made in a wide variety of ways, depending on the heating operation to be performed and the number of parts to be processed. Largely their design is merely the application of tool-engineering principles, whether hardening, brazing, soldering, or other forms of heating are required. Even though the generation of high-frequency induction heat is purely an electrical consideration, requiring a generator or oscillator to produce the output current, the actual applications become almost entirely mechanical and are limited, to some extent, only by the amount of ingenuity exercised in the method of handling a given part.

For some forms of heating operations, the fixture design may be relatively simple, requiring only a stud or a plate to support or centralize the workpiece within a heating coil. On the other hand, where small parts may be produced in high quantities and the heating cycle is exceedingly fast, it may become necessary to provide a highly mechanical fixture or feeding unit, such as belt conveyors, or automatic indexing attachments. Since high-frequency heating may be used advantageously in such fixture designs, the problem lies in providing an efficient means of transferring heat to the work as rapidly as is possible in the operation required.

Generally speaking, no fixed rules apply to tool design for induction heating other than the basic principles used for miscellaneous types of fixtures, or feeding devices for other forms of operations. One important consideration, however, is to keep all metal parts far enough away from the heating coils, or inductors, for the fixture parts themselves not to absorb the heat energy that should go into the work. A spacing of 2 in. or so is a safe allowance for operations requiring intermittent heating cycles, whereas a much greater distance is preferable where continuous heating is to be applied.

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Nonmetallic materials, such as pressed wood, asbestos board, plaster of Paris, glass, plastics, and other molded insulating materials, will be found satisfactory for fixture components adjacent to heating oils. Where intricate forms may be needed, cast plastics, such as those having a phenol formaldehyde base to which a catalyst is added, or the acetone-thermoplastic types, may be used advantageously. In cases where metal must be
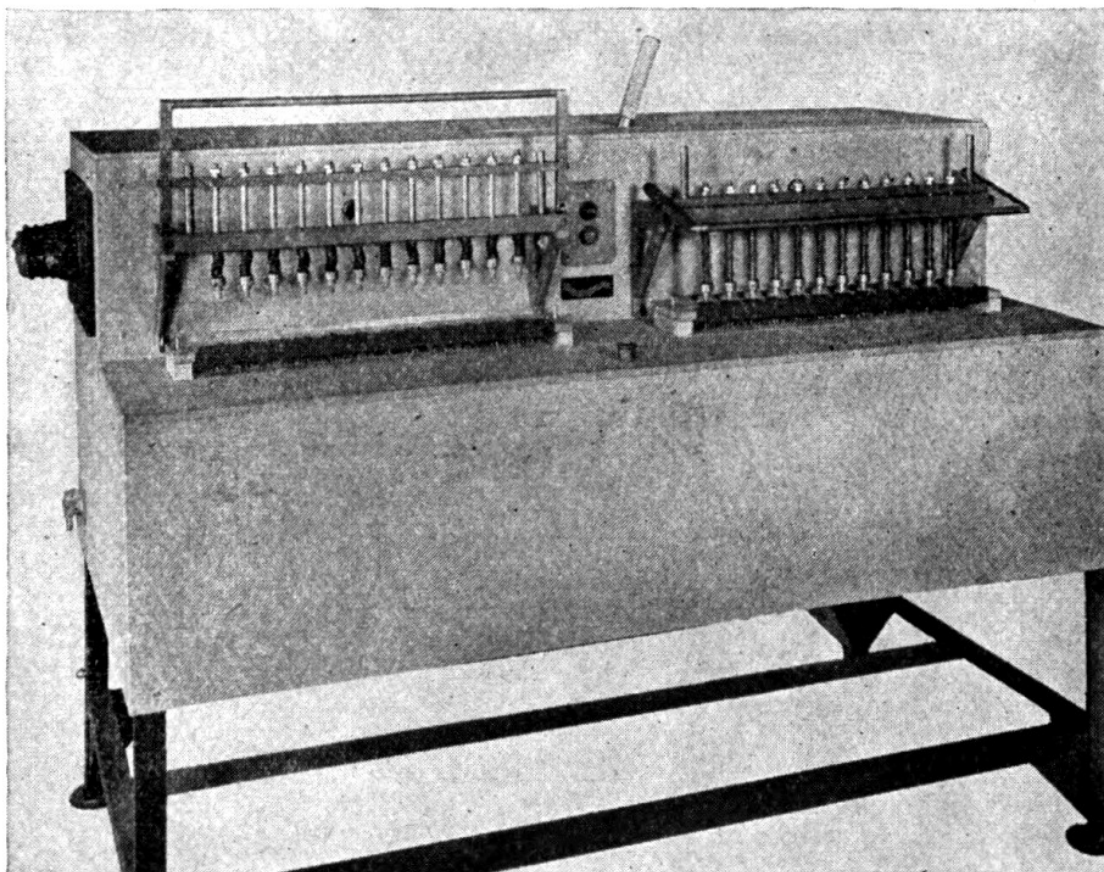

Fig. 181.—A multi-type brazing fixture arranged with two separate stations, each of which handles 12 parts simultaneously. (*Courtesy of Induction Heating Corp.*)

close to heating coils it is preferable to use nonferrous materials, such as brass or aluminum, which have a slower heat absorption. Nichrome, because of its low heat conductivity, also is good for such parts.

A fixture for multiple-brazing operation is shown in Fig. 181, in which 12 parts are handled simultaneously. The table is arranged with two complete fixtures, one of which can be loaded while the other is in use. The operation is that of brazing a silver disk to a sheet-metal sleeve, as illustrated at *A* in Fig. 182, which also shows details of the holding device and fixture.

The silver disk is previously coated on one side with a brazing alloy, so that it is necessary to apply only a small amount of flux at the joint prior to heating. The operation is carried out by placing 12 sleeves on an asbestos-board workholder, counterbored to nest the pieces as shown, and then locating the disks on them with the coated face down. The workholder then is located onto the table, being centralized by guide pins at each end. The induction coils, connected in series, over which the sleeves fit, are arranged to heat from the inside.

With the loaded workholder in place, the disks are held down against the sleeves by spring-controlled plungers. In order to prevent any heat conduction into the plunger, asbestos tips, rather than metal, are attached at the end of the plungers to make the actual contact with the work. The high-frequency generator for this setup is located at the left of the table and the power terminals are attached to the feed-through connectors shown at the left end. The brazing time for this operation is 22 sec.

Sometimes it is necessary to arrange induction-heating fixtures so that the work will drop down over heating coils, as illustrated in Fig. 183. Here, two drawn-steel shells are to be annealed. They are placed on the fixture when in the elevated position and then lowered over the coils shown directly below. The holding plate of the fixture is made of asbestos board and is provided with two counterbores into which the workpieces fit, so that they will be properly centralized in relation to the heating coils. The multiturn coils are series-connected by means of the jumper *A*, whereas the passage of water is made continuous by means of the hose connection *B*. The annealing operation is

Fig. 182.—Constructional details of the spring plunger used to braze silver disks to a sheet-metal sleeve.

required on these shells between draws. They are brought up to a temperature of 1400°F.

A representative design of fixture for hardening a localized surface on a receiver body at the location represented at *A* is illustrated in Fig. 184. The fixture and coil assembly are arranged for submerged quenching of the part. Four pieces are inserted into the fixture, receiving their alignment from sleeves. These pieces rest on a slide plate, located on the bottom of the fixture. The series-type heating coil is shown at *B*. With the
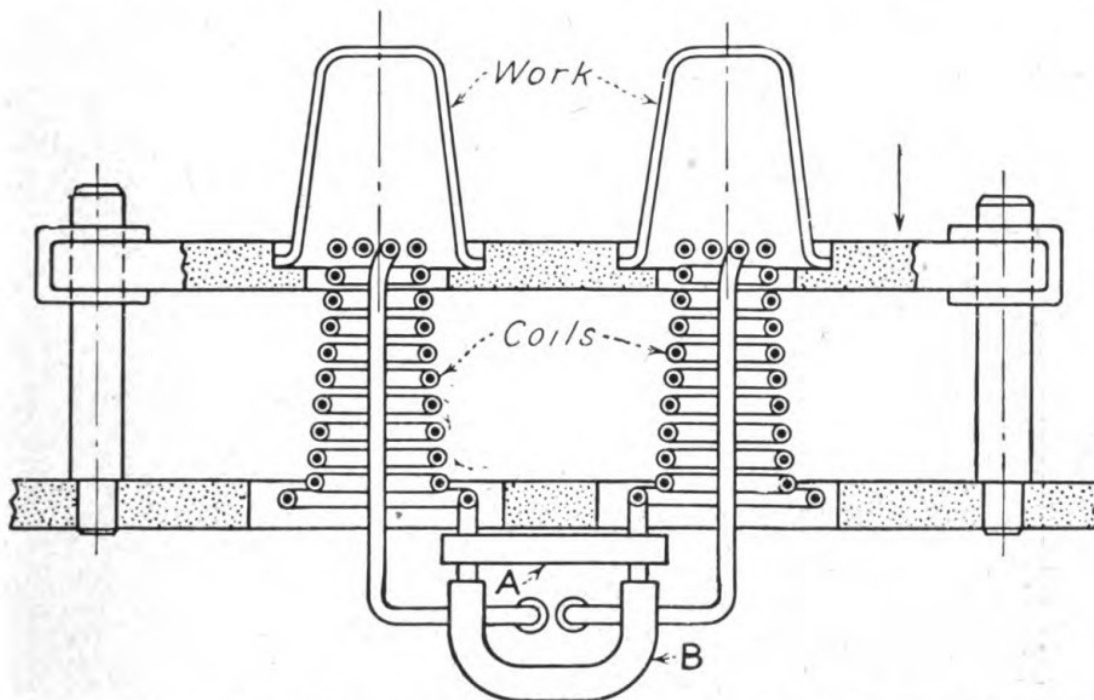
FIG. 183.—A vertically operated fixture arranged so that the work is lowered over the heating coils. The operation comprises the annealing of two sheet-metal shells.

four pieces in position, the heat cycle is started. Then when sufficient heat has been applied the operator pulls the sliding plate forward by means of the handle *C* and the parts slide through an opening into the quench tank, located directly under the top of the table. A pilot light, mounted on the panel directly behind the fixture, is on during the heating cycle and serves as an indication for the operator to quench the parts when the light goes off.

A two-station fixture for the heating of harness buckles requiring drop forging is illustrated in Fig. 185. The unit is provided with a change-over switch so that while a part in one side is being heated, the operator can unload and load the opposite side. The flat steel section is heated to a temperature of 2200°F.,

requiring only 12 sec. for a complete cycle. In this installation the coil is surrounded by an asbestos-board shield, which has an opening at the front through which is inserted the section of the part to be heated. The fixture member, which holds the buckle, is mounted on a tranverse slide, so that the loading is done prior to inserting the work into the coil. This unit is located adjacent to a power press, into which the heated buckles are transferred for the forming of an eye.
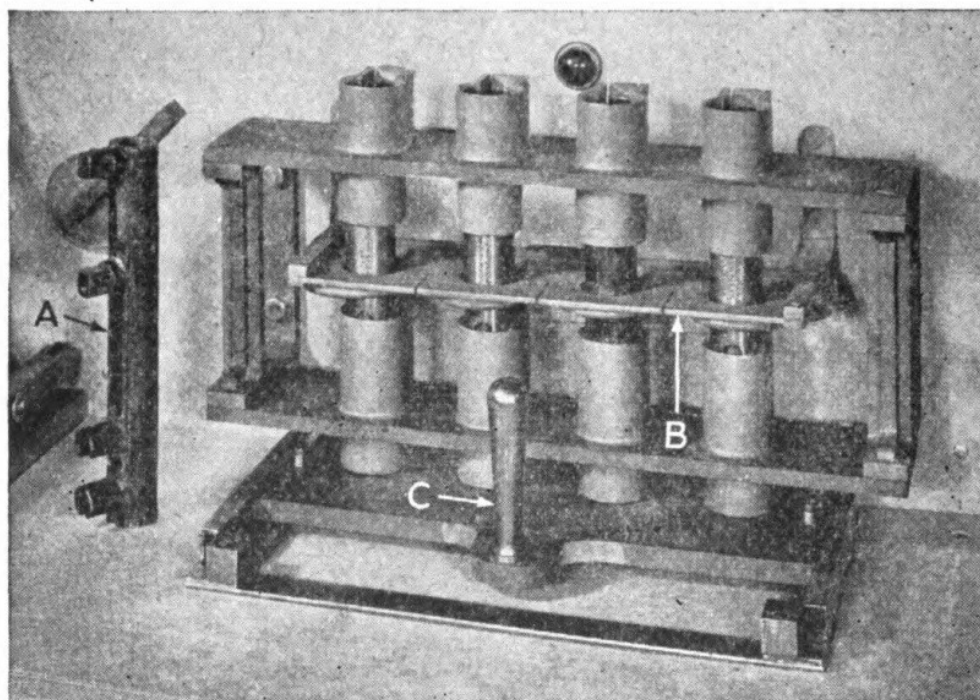
Fig. 184.—This fixture is arranged with a hand-operated slide, which can be withdrawn to permit the heated parts to drop into a quench. (*Courtesy of Induction Heating Corp.*)

A fixture arranged to facilitate the handling of a long part requiring heating at one end can be designed, such as that illustrated in Fig. 186. The operation shown represents an installation for the heating of the hub end of a propeller blade in a motor-generator unit. The propeller blade is clamped into a fixture which, in turn, is mounted on a track, so that the hub end of the propeller can be readily inserted and withdrawn from the induction coil, as shown at the right. In this operation the hub is heated to a temperature of 2000°F. in approximately 30 sec., whence it is immediately removed for forging. The fixture is provided with a quick-operating clamp, so there will be very little loss of time in removing the propeller from the fixture carriage.

The generator is provided with two heating stations to provide for maximum output.

When hardening long shafts, it is often desirable to heat only a small area at a time and to use a progressive-feeding fixture,
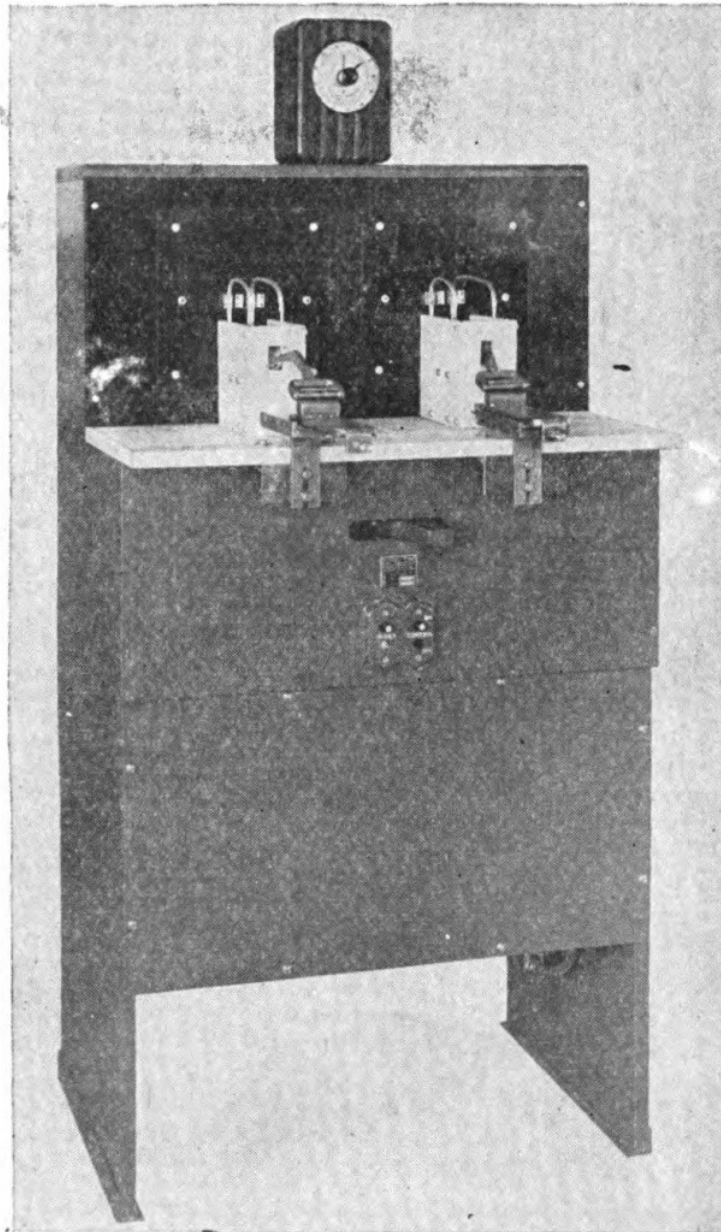
FIG. 185.—A two-station heating fixture arranged with horizontal-sliding work holders. The parts are heated to a temperature of 2200°F. for forging. (*Courtesy of Ecco High Frequency Corp.*)

such as that illustrated in Fig. 187. The work in this case is suspended between adjustable centers, which, in turn, are mounted on a slide. Control of the slide is by means of a small hydraulic cylinder, operated from water pressure, metered by a

needle valve to provide the correct rate of feed. The quench ring, made of plastic, is placed adjacent to the induction coil, so that as the heated portion of the shaft progresses through the
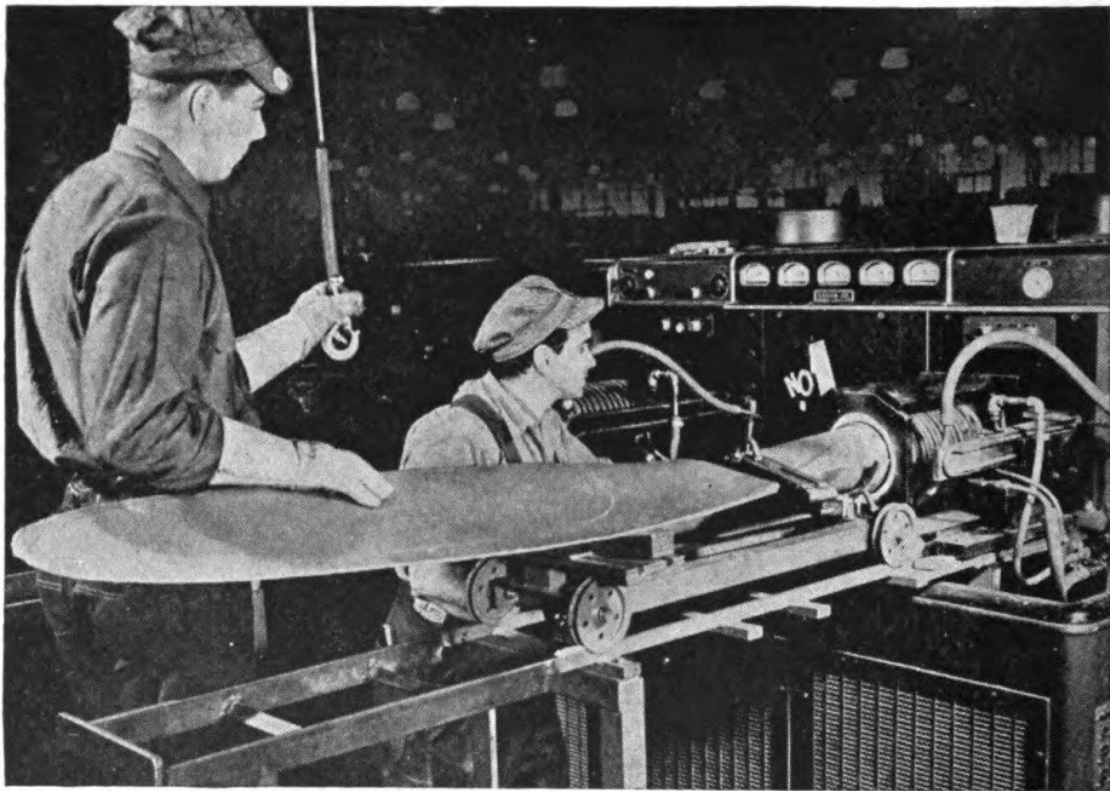
Fig. 186.—An induction-heating setup in which the work is mounted on a sliding fixture to facilitate handling. The work is clamped in the fixture, and then advanced into the coil for heating of the hub area. (*Courtesy of The Ohio Crankshaft Co.*)

coil it is quenched immediately. A two-station timer is used to control the heat and quench cycles, whereas the feed to the slide is continuous as long as the high-frequency generator is energized, the control being by means of a solenoid-operated valve.
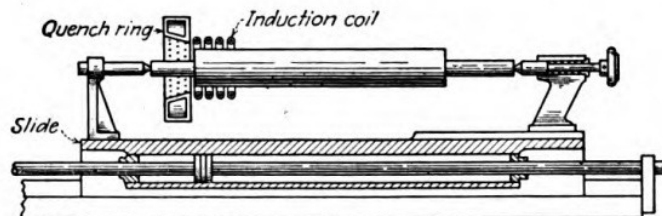
Fig. 187.—A typical arrangement used for the progressive hardening of long shafts. The work passes through a heating coil, and then is automatically spray-quenched.

A fixture assembly for hardening shafts and similar parts is illustrated in Fig. 188. It consists of a base to which may be attached V blocks, or supports to align and centralize the part

to be hardened. Also on the base is mounted a quench-ring assembly, provided with two water connections which are connected to the water supply. Operation of the quench is usually timed by means of a solenoid-operated valve. The quench ring should be made of a nonmetallic material, or if a metal is used it can be aluminum or some other nonferrous material of low heat-absorbing properties.

Fixtures of this type can be made in standard sizes; and various standard parts, such as the base and quench ring, can be carried
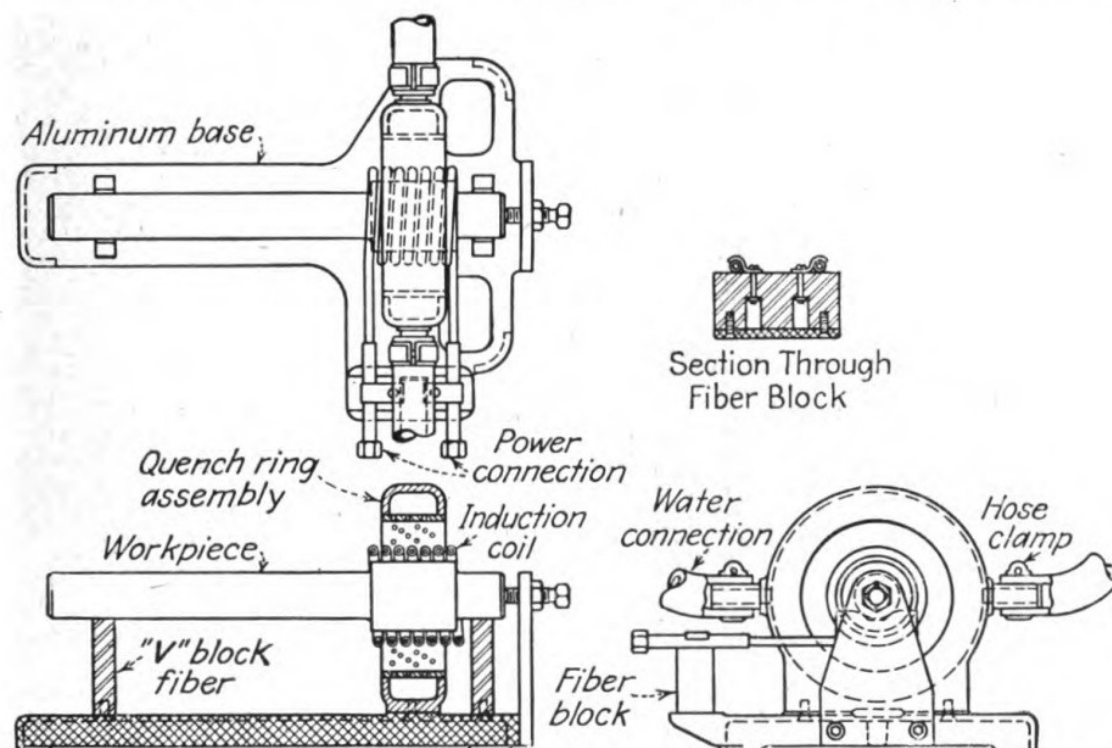
Fig. 188.—A fixture assembly, including base, quench ring, and heating coil, which is suited to a large variety of shafts requiring localized treatment.

in stock, so that new fixtures can be quickly assembled when required. The cost of the parts is relatively low. The base can be made of aluminum in order to facilitate handling the fixture or, if preferred, it can be made of a molded or laminated plastic.

A two-station work table complete with fixture as used for performing two different operations is illustrated in Fig. 189. Both fixtures are of the elevating type, their motion being controlled by air cylinders.

The operation at the left-hand side is arranged for the hardening of the outside surface of a tapered valve. Two pieces are placed in the fixture, then when the platform is elevated the parts enter the series-type heating coil shown directly above. An air-

hardening steel is used for these parts, so that at the completion of the heating cycle an air blast is engaged by means of a timer, which cools the pieces rapidly.

The fixture shown at the right is arranged for the hardening of valve inserts, in which the inner surface is heated and hardened by means of an internal-type coil. The procedure for this operation is practically the same as for the other in that the work is elevated into the coils. A sleeve is applied to the coil assembly as an assurance that the work will be properly centralized.
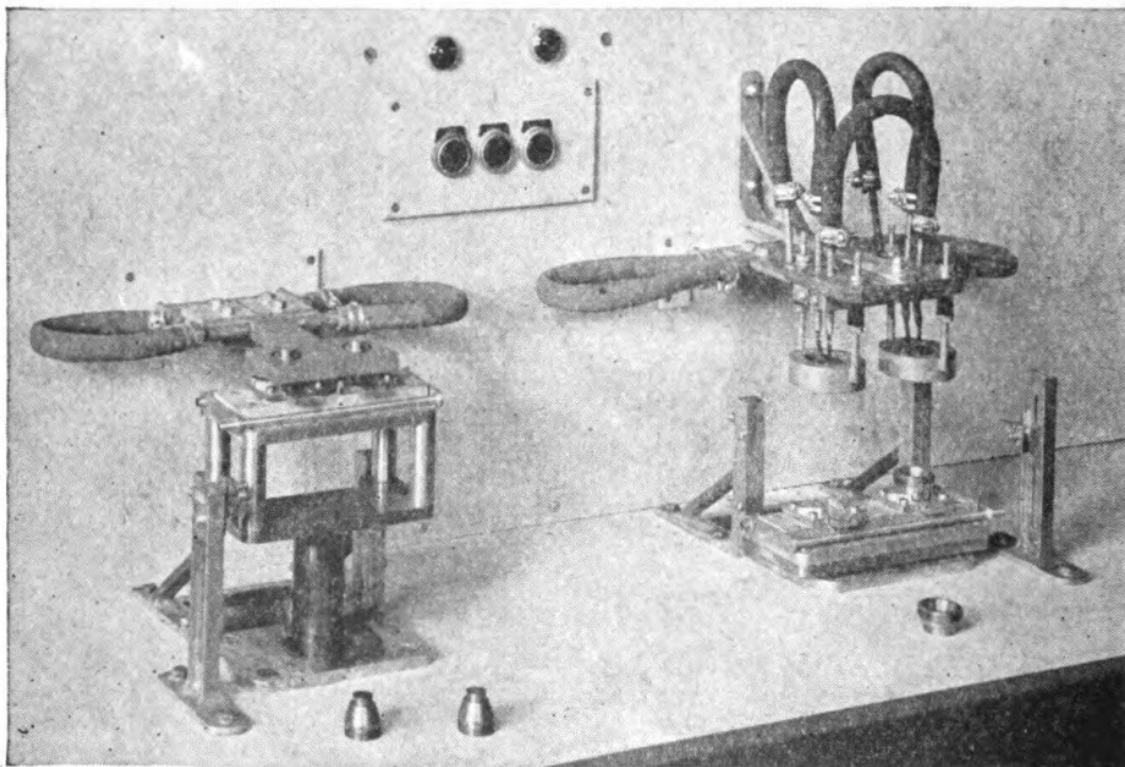
Fig. 189.—A well arranged two-position worktable, provided with vertically operated fixtures, as used for the hardening of small steel parts. (*Courtesy of Induction Heating Corp.*)

An induction-heating setup for hardening the heads of screws is illustrated in Fig. 190. The fixture is of the continuous-rotary type and is provided with several work-holding plates hinged to a central hub. The parts to be hardened are placed on these plates, as shown at the left, and continue their course through a hairpin-shaped coil, as shown at the right. After the heating has been completed, the fixture plate leaves its supporting member and tips over so that the heated setscrews automatically drop into the quenching bath, directly below. The operation is performed in a 2-kw. generator, at a rate of 2,700 pieces per hour.

The hardening is confined to a depth of about ⅛ in. at the slotted end, whereas the remainder of the setscrew is unchanged.

A semiautomatic-type fixture, provided with electrical controls for hardening the ends of caps, six at a time, is shown in Fig. 191. The pieces to be heated are placed on an elevating fixture plate, as may be seen in the upper illustration at *A*, in its loading position. When the push button is engaged, the fixture plate is raised by means of an air cylinder, placing the caps in the heating
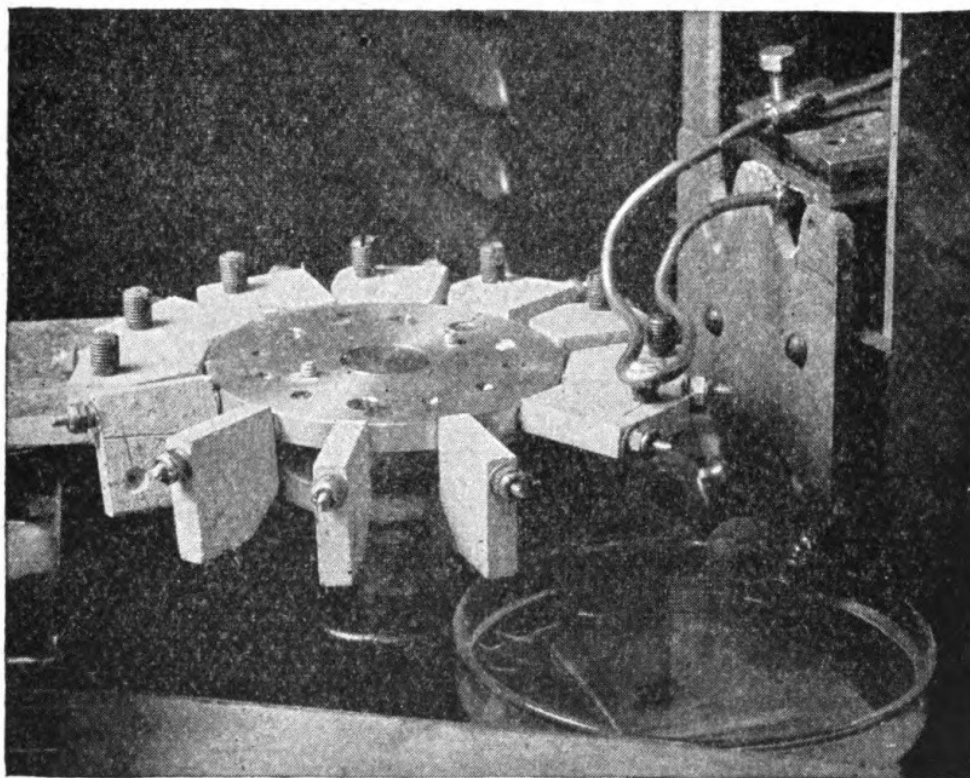
FIG. 190.—A rotary-type fixture arranged for the progressive heating of small parts requiring hardening. (*Courtesy of Radio Corporation of America.*)

inductor, as shown at *B* in the lower illustration. As the fixture plate is elevated to its heating position, it engages a limit switch which automatically starts the heating cycle of the high-frequency generator.

Directly above each heating chamber of the inductor is located a quenching tube through which water passes after heating has been completed. Both the duration of the heating and quenching cycles are controlled by an automatic timer, as well as the downward stroke of the fixture plate after the quench has been cut off. Details of the inductor are shown in Fig. 192. It is made from a copper casting, provided with cored openings to provide the correct coupling between it and the workpieces.

In Fig. 193 is shown a versatile heating unit for progressively annealing rods made of precious metals. This unit is equipped with a variable-speed drive, which provides feeds from 6 in. to
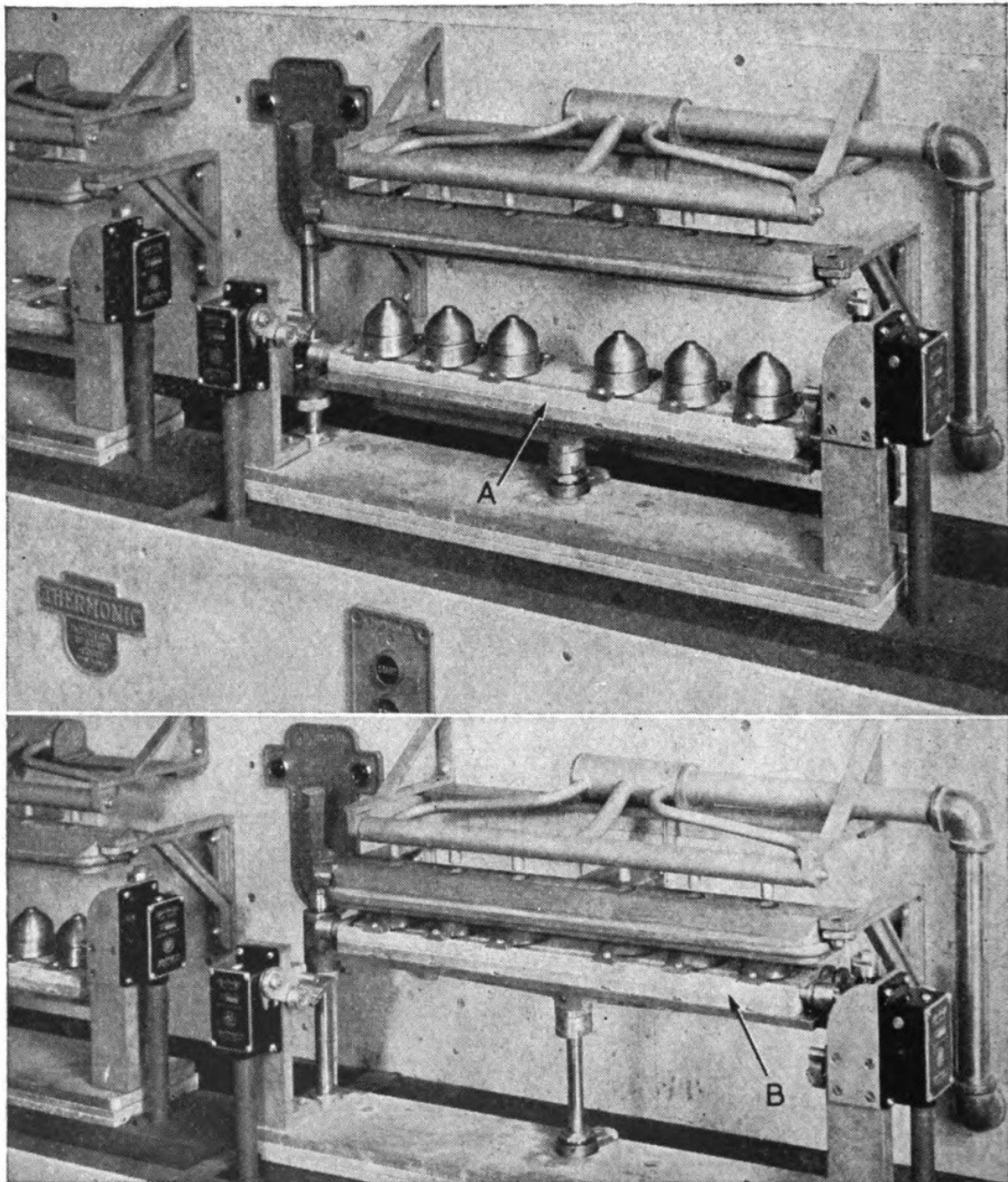
FIG. 191.—A semiautomatic fixture used for the hardening of caps, provided with a vertically operated platform so that the parts are elevated into a cast-type inductor. Heating and quenching are automatically controlled. (*Courtesy of Induction Heating Corp.*)

12 ft. per min. The work to be heated passes through a quartz tube, on the outside of which is located a multiturn copper-tube induction coil. The feeding mechanism is provided with power-driven feed rolls at both ends. As the metal bar to be annealed

pàsses beyond the induction-heating zone, it enters a quench zone, shown at the right, where a suitable water spray is provided.

When units of this kind are used in connection with continuous-feed operations, there is a decided advantage in the application of high-frequency heat in that the current can be turned off instantly . should there be any interruptions through other operations. Normally, with other means of heat, there would be a danger of burning the metal in the event that the feed should stop. This feeding unit is adaptable to various sizes of rod and
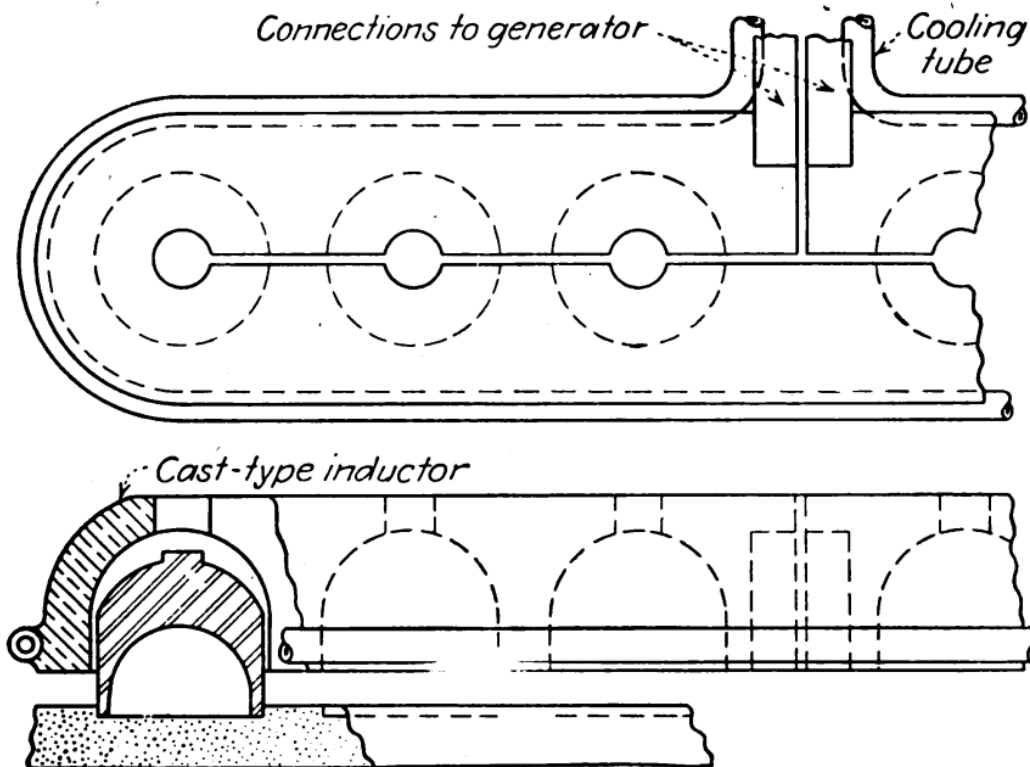
Fig. 192.—Constructional details of the cast-type heating inductor used in connection with the hardening of six caps simultaneously.

is arranged so that quartz tubing of different diameters, as well as suitable coils, can be substituted for those shown.

A rotary-type fixture used in induction heating is illustrated in Fig. 194. The operation is that of hardening valve tappets. Both the seat and the shoulder are heated to a temperature of 1500°F. This is accomplished as the work passes through a specially formed inductor. As soon as the part has become heated, it automatically indexes to a jet quench position, and then drops into a chute whence it is removed by means of a conveyor to the next operation.

The production for this operation is approximately 6,000 pieces per hour. The high-frequency current is supplied by a 200-kva.

motor-generator set.   This type of fixture is useful in a wide variety of small parts requiring localized heating.

An indexing-type fixture for hardening the ends of gear shifters may be seen in Fig. 195.   For this part only the fingers
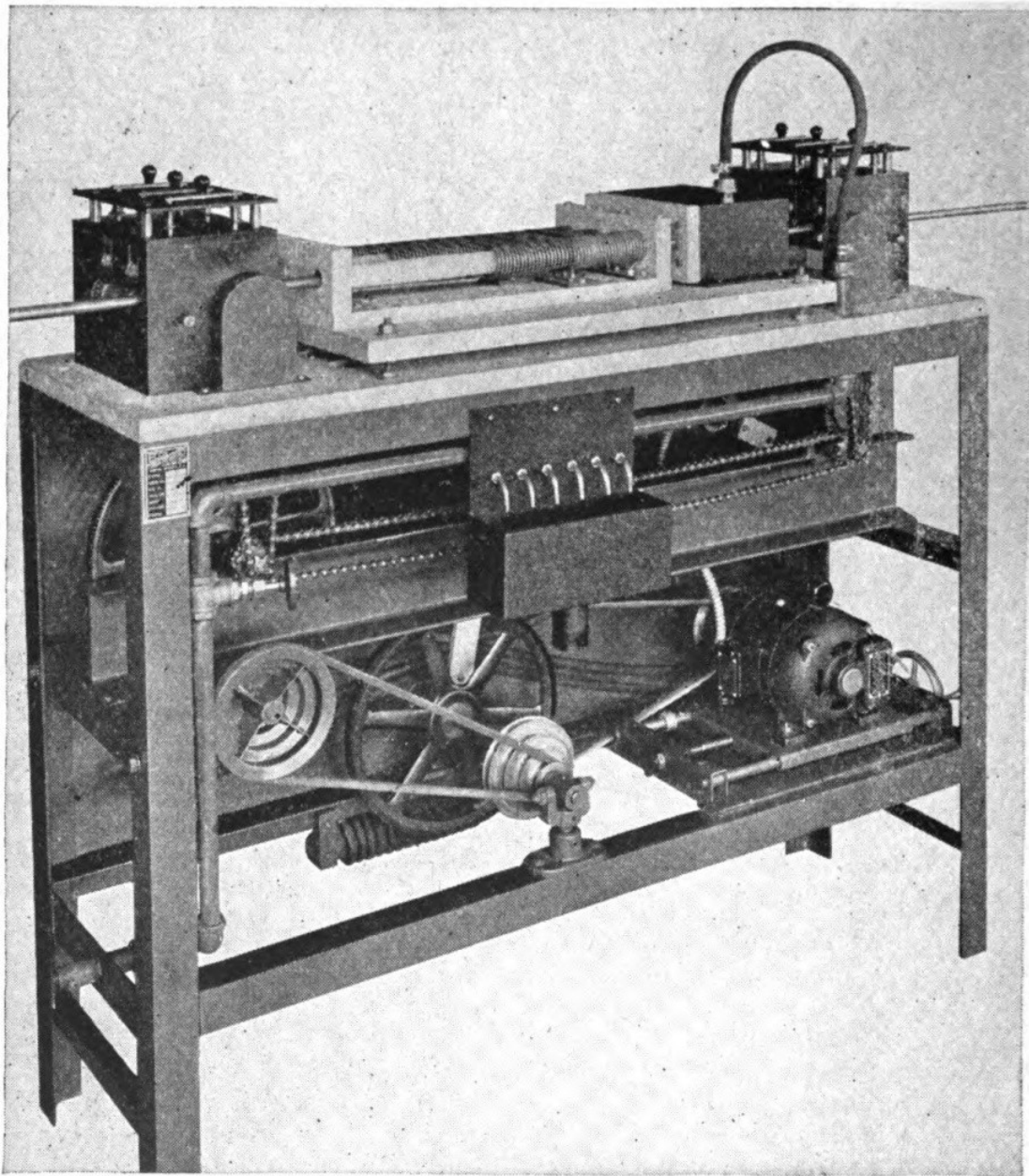
FIG. 193.—A continuous-feed mechanism used for the heating of small rods and bars of nonferrous alloys.   Provision is made for atmospheric control. (*Courtesy of Ecco High Frequency Corp.*)

require hardening, and the coil used is a series type, with two heating areas into which the projecting ends of the workpiece enter.   The fixture plate, arranged to hold four shifters, is mounted on a slide which moves in and out in relation to the 90-deg. indexing of the fixture plate.   The slide is cam actuated
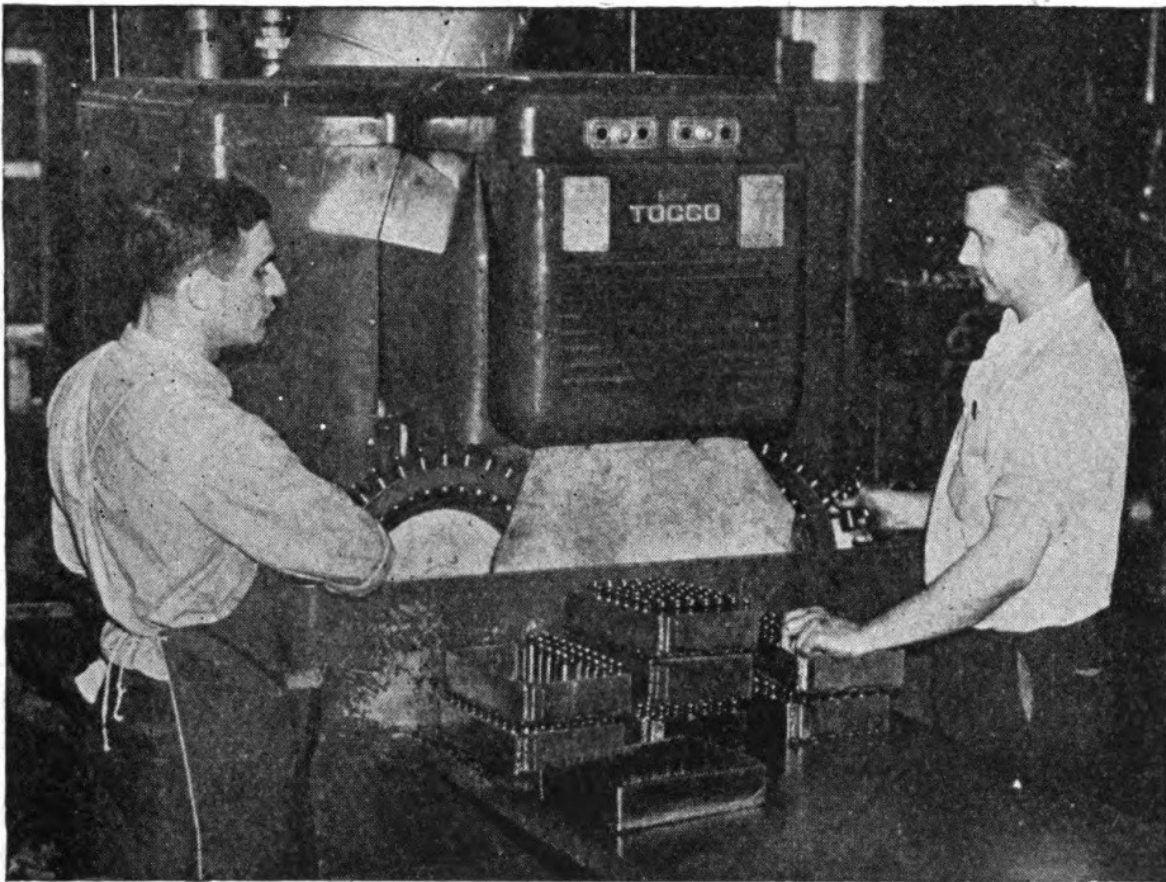
FIG. 194.—A continuous-type feeding fixture of rotary design arranged for hardening the ends of push rods, at the rate of 2,500 pieces per hr. (*Courtesy of The Ohio Crankshaft Co.*)
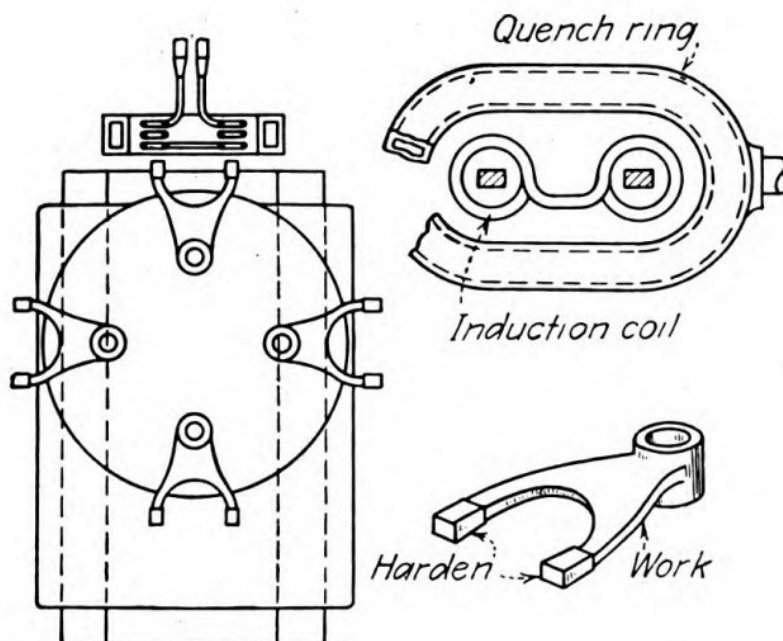
FIG. 195.—An automatic indexing fixture of the type shown can be used for the selective hardening of small parts, such as the shifter shown.

and the plate index is operated by a geneva cam, so that once the power is applied it is only necessary for the operator to load and unload the parts on the front station of the fixture. Quenching is effected by a formed plastic-type quench ring, whereas the heating and quenching portions of the cycle are tied in with the dwell of the fixture and controlled by a limit switch actuated when the slide moves forward. The fixture is timed to make a complete cycle in 7 sec.
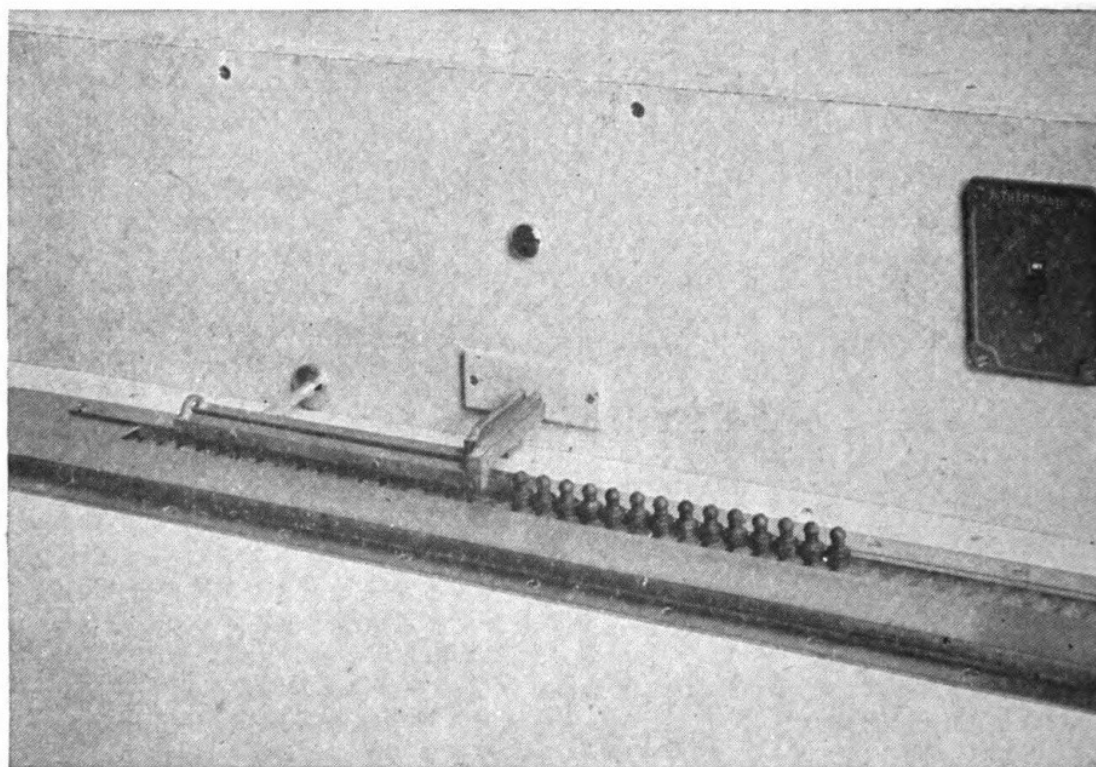
Fig. 196.—A conveyor-type hardening installation arranged so that the work passes through two parallel inductor bars for heating, after which the heated pieces are ejected for submersion quenching. (*Courtesy of Induction Heating Corp.*)

This same type of fixture can be used for a wide variety of induction-heating operations, whether for hardening or brazing. The shape and size of the part in question will, of course, determine its application, but it will be seen that many adoptions are possible, such as hardening the ends of pins, small shafts, and bearings, as well as the brazing and soldering of small assemblies, in which case the quenching cycle is not required.

An example of a progressive-feeding arrangement for high-frequency heating of small ball joints is illustrated in Fig. 196. In this setup a continuous conveyor is in operation, which, in turn, is provided with a number of work-holding nests. The ball

joints are placed on the conveyor at the right and then pass through the parallel-type heating inductor, where the spherical surface becomes heated. Immediately upon reaching the end of the inductor, the parts are ejected and fall into a quench bath which is located under the table.

The inductor for this operation consists of two bars of copper formed to resemble the contour of the spherical surface to be heated, as illustrated in Fig. 197. For passage of the cooling water, holes are drilled through the bars at the upper section as shown. At one end of the bars a copper-tube jumper is provided for the passage of high-frequency current, whereas at the opposite end suitable offsets are made for connection to the high-frequency generator.
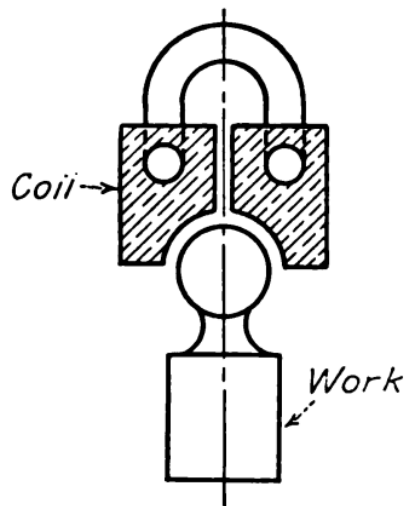
FIG. 197.—Cross-sectional view of the inductors illustrated in Fig. 196, showing their relationship to the workpiece.

In an operation of this kind there are two factors that can control the output, assuming that a certain power source is available. One of these is a coupling, and the other is the speed of the conveyor. For example, if the conveyor had a fixed speed and if the parts appeared to reach too high a temperature, it would be necessary only to raise the inductor slightly in order to obtain the desired lower temperature. On the other hand, if a variable feed were available, it then would be possible merely to increase the speed to suit the resultant heat at the output end. In this operation, the production rate is 2,500 pieces per hour.

Another interesting type of automatic-indexing fixture for induction hardening is illustrated in Fig. 198. The part to be heated is a small steel bearing requiring hardening on the outside surface, as shown at *A*. The parts are fed by hopper to the indexing plate *B*, which contains a number of work-holding stations. Under this plate and directly over the heating coil is a fixed member with an opening that lines up with the corresponding hole in the index plate. In operation, as the work-holding plate indexes, a workpiece drops down into the heating coil. To provide insulation, as well as to centralize the part while it is heating, a pyrex-glass tube is placed within the coil. Since glass has no resistance to the passage of high-frequency

current, the heating of the piece within the coil is unaffected by its use.

At the end of the heating cycle, which in this case is less than 1 sec., the trip *D* is withdrawn by a solenoid, which permits the heated part to drop into the quench directly below.   Details of the induction coil are shown at *E*, while at *F* may be seen an enlarged section showing the relation of the coil, glass tube, and workpiece.
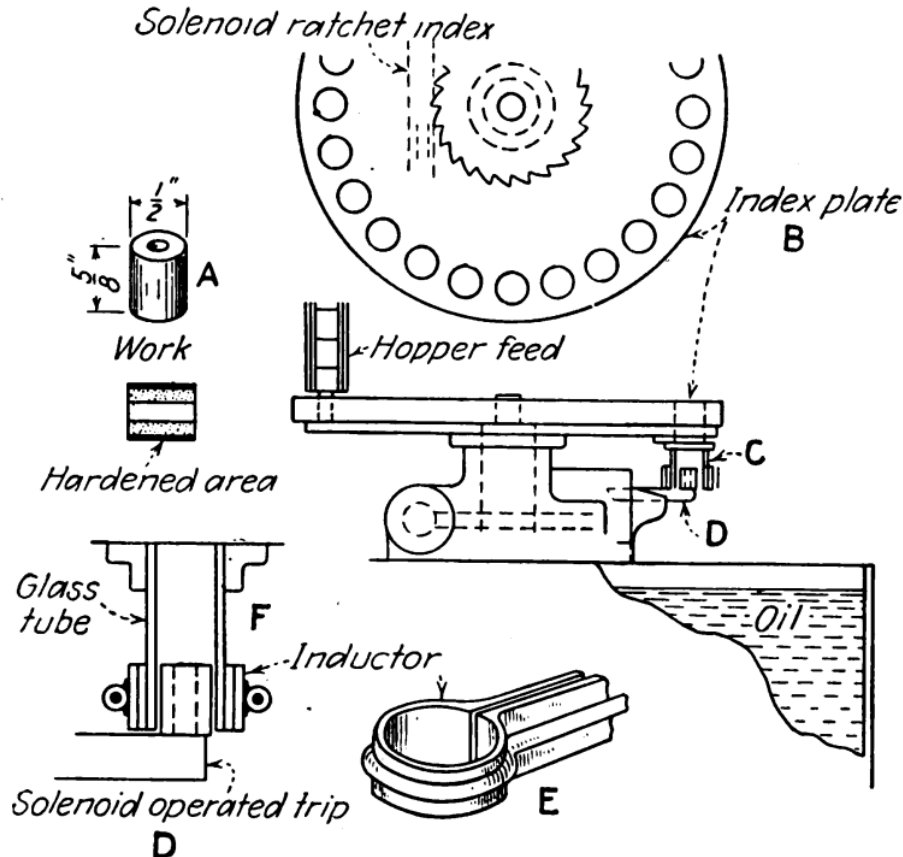

Fig. 198.—Automatic-type indexing fixture, which can be arranged for the hardening of miscellaneous small parts, such as pins and bushings.   The parts are automatically dropped into a quench after being heated.

The fixtures that have been described herewith are representative of designs which can be adapted for a variety of brazing, soldering, and hardening operations, through the use of high-frequency induction-heating generators.   High frequency as a means of heating metal parts is rapidly finding broader uses in industrial plants and unquestionably will have a marked effect on manufacturing procedures, as well as engineering design in some fields.   To apply this form of heating to the best advantage will always require a full knowledge of the mechanical needs to ensure efficient processing, and this will largely include modern fixture design.

CHAPTER VII

MISCELLANEOUS INDUCTION-HEATING APPLICATIONS

High-frequency induction heating can perform a wide variety of industrial functions in addition to hardening and joining, although these two fields constitute its outstanding uses. Among other uses are the heating of parts for forging, stress relieving and annealing, drawing and tempering, melting of metals for casting, bonding of various materials, paint drying, flowing of tin plate, bombarding of radio tubes, heating for straightening operations, sintering of powdered alloys, and various fusing needs.

It would be difficult to describe the many and varied applications for high-frequency heat, together with the equipment adopted for their use. A few representative examples are given herewith to show that inductive heat can be made to cover a broad field and that with suitable operating facilities many far-reaching problems can be solved.

One of its oldest uses is in the bombarding of glass-enclosed radio tubes. High-frequency generators have been used for this purpose for many years, and the successful production of radio tubes has been considerably advanced through their use. In operation, a heating coil surrounds or lies adjacent to the glass enclosure of a tube, during the degassing operation. The metal elements in the tube are heated to a high temperature, at the time that the vacuum is created. The fact that high-frequency current can pass through the glass jacket makes possible this heating operation, which would be difficult to equal by other means. Without fusing off the elements in this way, a radio tube would have very little life.

High-frequency heat has many uses in connection with annealing. In Fig. 199 is shown a setup for annealing the open ends of 105-mm. steel cartridge cases. Two work stations are provided, one of which is loaded while the other is in use. The part, because of its nature, requires elevation into the heating coils. The fixture, which is relatively simple in design, is

mounted on an elevating platform, the motion of which is controlled by an air-operated cylinder.   After two cases have been placed on the work-holding nests, the air valve is engaged, so that the work is elevated into the heating coil.   This coil is formed from flat copper strip and provided with a copper tube around the center section for cooling purposes.   The annealing temperature for this operation is approximately 1400°F., and the cycle requires but a few seconds for completion.
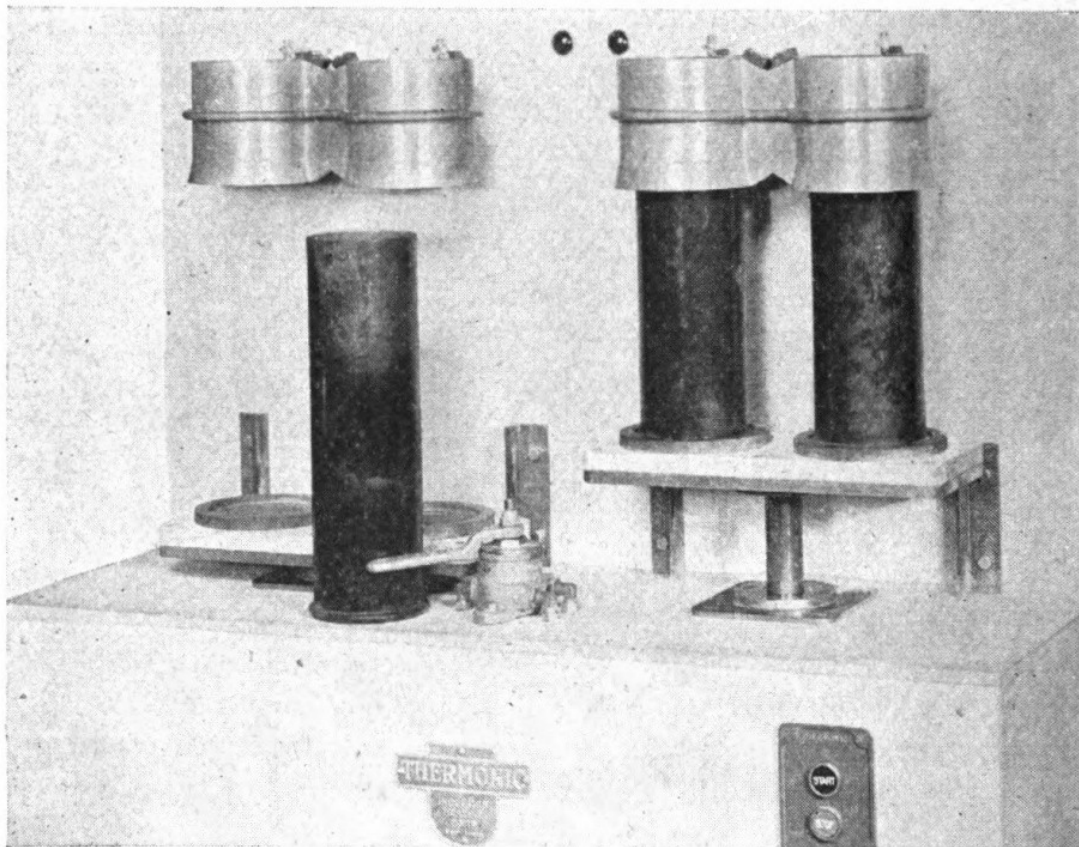
Fig. 199.—A two-station fixture arranged with vertically operated work carriers, used for the annealing of cases.   (*Courtesy of Induction Heating Corp.*)

A two-station induction furnace for heating the noses of 5-in. diameter steel shells is illustrated in Fig. 200.   The shells are heated to 1850°F. for forging.   The unit is located next to an upsetting machine, so that the heated shells are easily transferred from the induction heater to the forging die.   The shell has a wall thickness of $9/16$ in. and is heated back for a distance of $1\frac{1}{2}$ in.   Power is supplied by a motor-generator set, rated at 75 kw., and the heating time is $1\frac{1}{2}$ min.   To keep an upsetter in operation it is usual to have a series of two or three induction furnace units arranged to feed one upsetter, so that a heated shell can be turned out in 30 sec.
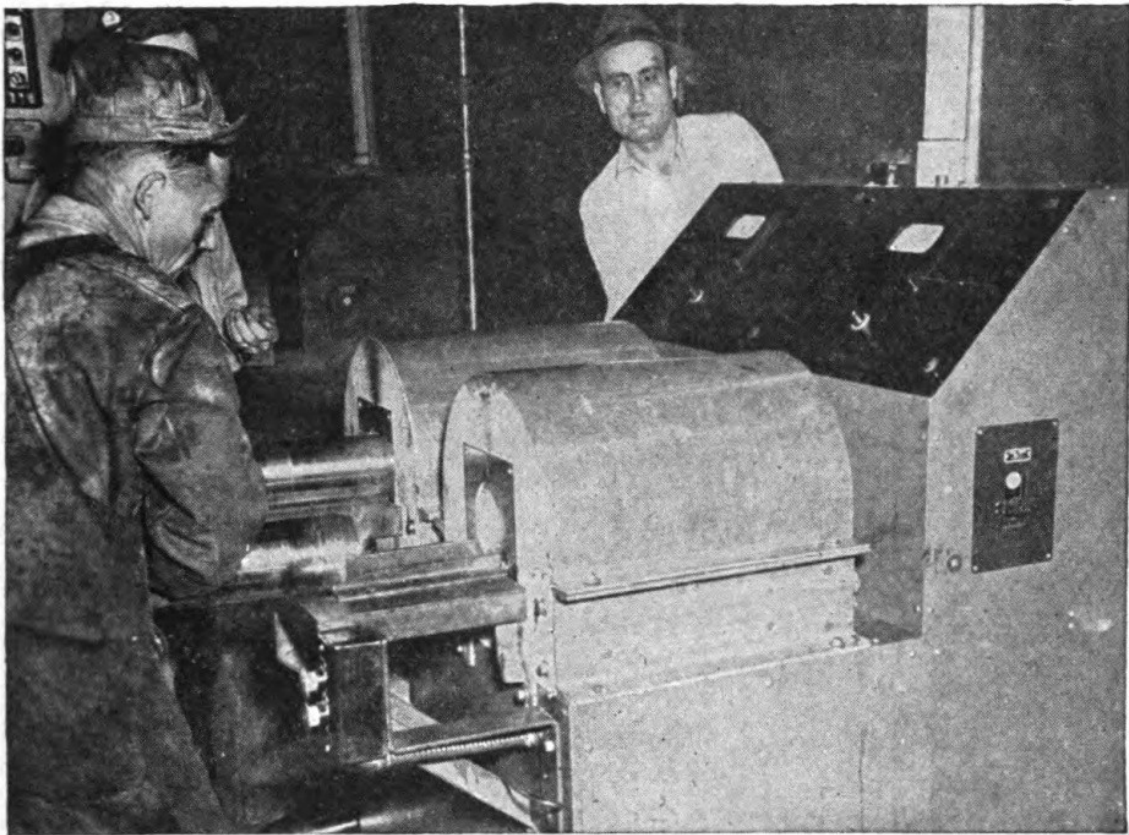
FIG. 200.—The heating unit of a motor-generator set used in connection with the forging of shells.   (*Courtesy of Ajax Electrothermic Corp.*)
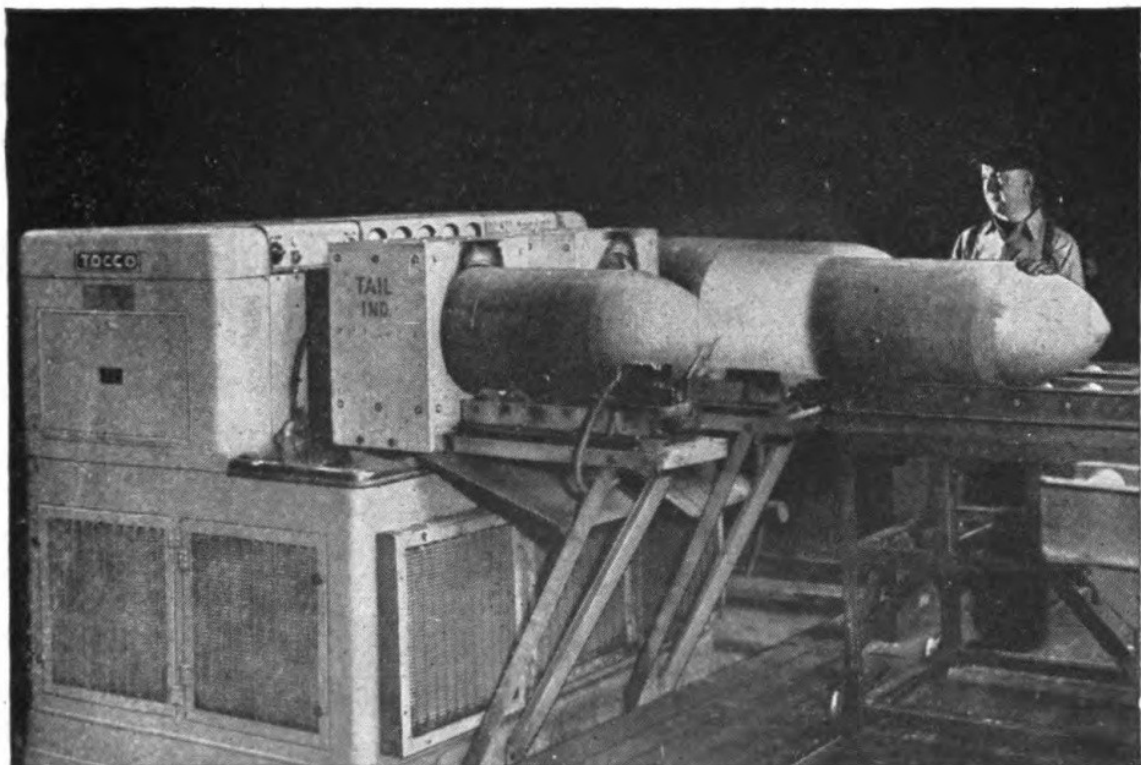
FIG. 201.—A 200-kw. motor-generator unit set up for the heating of large bombs, which require heating at one end to 2100°F., in a spinning operation. (*Courtesy of The Ohio Crankshaft Co.*)

The application of an induction generator for the heating of 500-lb. bombs, which require spinning at a temperature of 2300°F., is illustrated in Fig. 201. The generator is equipped with two separate heating units, which are used alternately. The induction-motor-generator set used for this operation is **a**
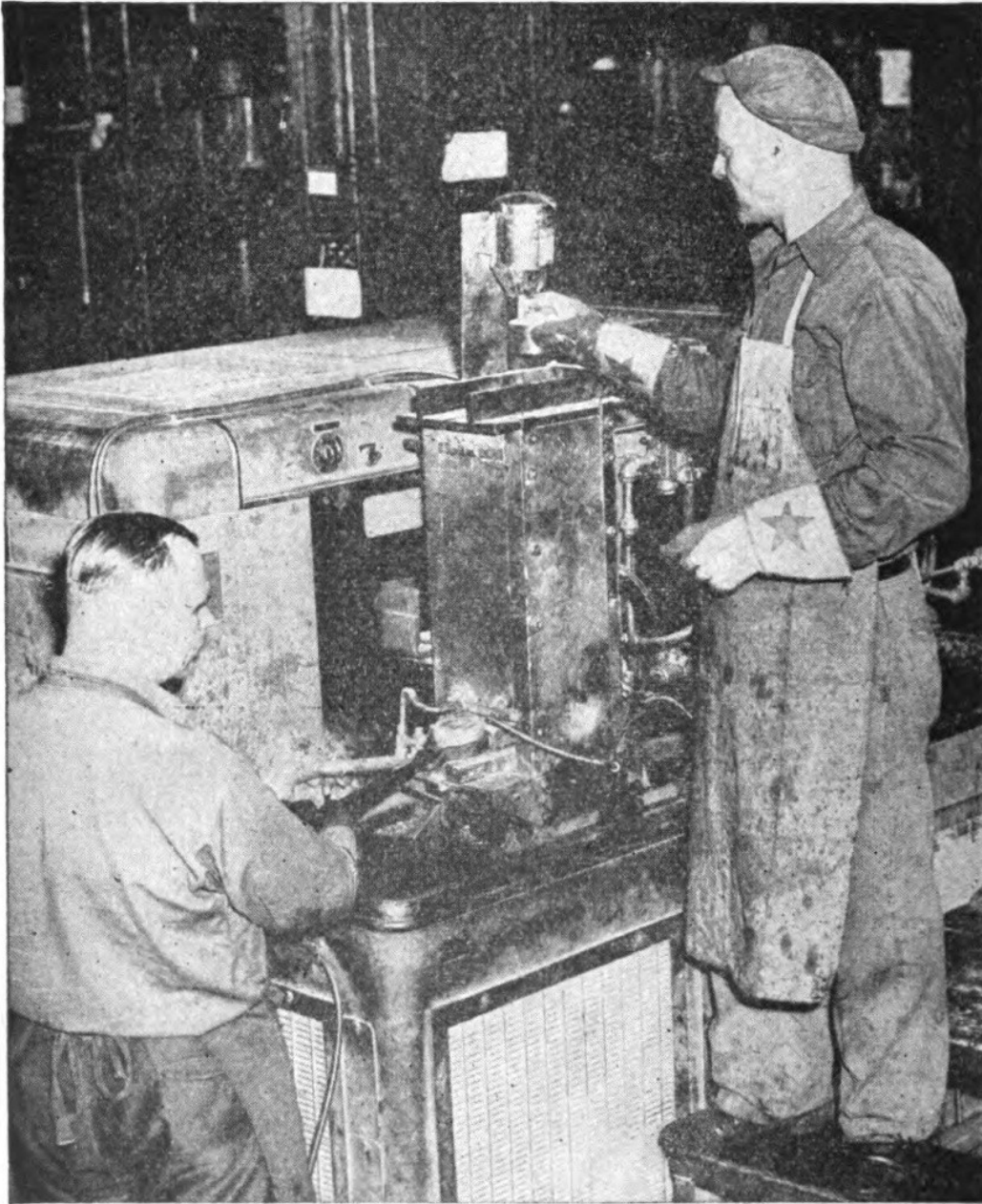
FIG. 202.—A progressive-heating fixture used for the treatment of cups which require forging.   (*Courtesy of The Ohio Crankshaft Co.*)

200-kw. 3,000-cycle unit.   The cases are made from heavy steel piping and are heated first for the shaping of the nose, then for the forming of the tail.   Spinning follows each heating cycle. Since the high heat is confined to the end area of each pipe section, the casings can be handled by operators without the

use of tongs. Conventional furnace methods require 5 to 6 min. for heating, whereas the induction method requires only 55 sec.

Another high-heat application of high-frequency heating, used in connection with drawing sheet-metal cases, is illustrated in Fig. 202. The operation includes the heating of a slug to a temperature of 2000°F. The slug is inserted at the top of the fixture, as shown by the operator at the right, and then automatically ejected at the left after it has reached the forging temperature. From this heating cycle the cup is drawn to a depth of 4 in. and then, while still hot, is drawn to a final depth of 6 in. without any subsequent heat being necessary.

The induction-heating generator is located conveniently at the drawing presses, and the heating operation is timed so that the presses are kept in constant operation, producing approximately 300 pieces per hour. The fixture itself holds twelve slugs, and one heated part is produced every 12 sec.

One of the advantages of this form of heating is the fact that very little or practically no scale is produced on the surface of the part, which has a marked effect on the life of the drawing dies. Since the abrasive action of the scale is detrimental to press tools, the elimination of the usual heavy scale is an asset in forging and drawing operations.

Still another advantage in an operation of this kind is the fact that should the presses for any reason be shut down the heating generator could easily be turned off to keep the parts within the heating inductor from being overheated. Contrasted with former methods of using a radiant type of furnace, where many cups were heated at one time, the chances for spoilage are greatly minimized by high-frequency heat.

Flowing Tin Plate. High-frequency heating at 200,000 c.p.s. from a 200-kw. high-frequency generator, to melt tin electrolytically deposited on a steel sheet, has made possible the saving of tin, ordinarily used for plating, and also has improved the corrosion protection of plated sheet. The process is arranged to flow 12 sq. ft. of tin in 0.7 sec., much faster than was previously practical with gas furnaces or vats of hot oil. A diagram of the tank line, which provides for continuous electrolytic tinning, fusing, and sheeting, is illustrated in Fig. 203.

This high-frequency method of using tin makes practical the final step in electrolytic tinning, which saves two-thirds of

PLATING ZONE REFLOW ZONE SHEARING ZONE
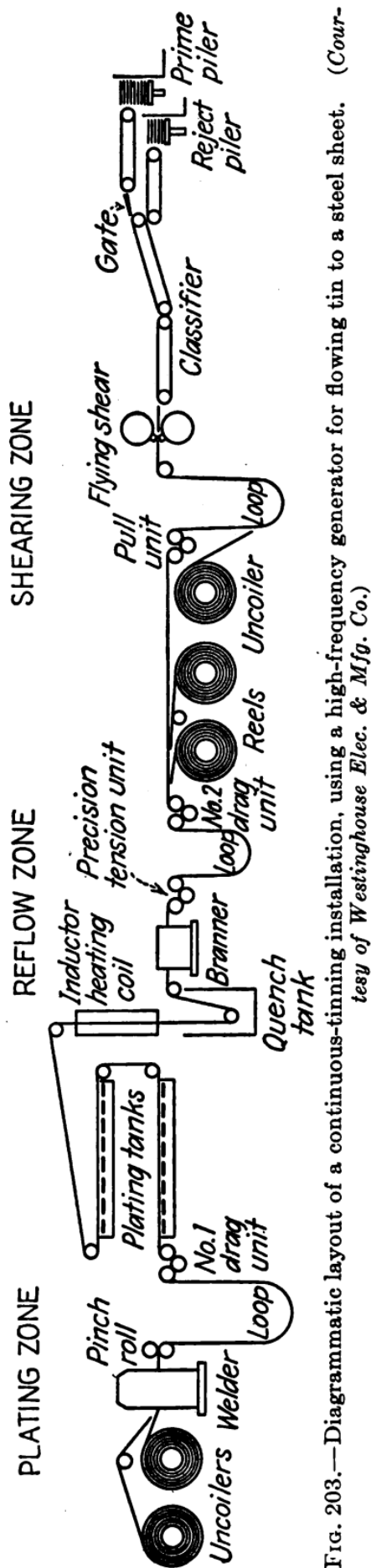
FIG. 203.—Diagrammatic layout of a continuous-tinning installation, using a high-frequency generator for flowing tin to a steel sheet. (Courtesy of Westinghouse Elec. & Mfg. Co.)

the tin normally required. The electrolytic coating of only 30/1,000,000 in. on each side of the strip, now possible, cuts 60/1,000,000 in. off the coating applied by the former hot-dip process. As the power input to the inductor coil, which determines the amount of heat generated, can be immediately and automatically adjusted to correspond with any change in the speed of the strip, the proper temperature to melt the tin is maintained and oxidizing of the strip is eliminated.

Tin plate must have high corrosion resistance to make possible the packing of foods containing acids. To provide the steel strip with adequate protection, the tin must be heated to the fusion point, so as to flow into a smooth, homogeneous mixture. Electrolytically deposited tin forms a granular, dull gray surface, which is not highly corrosion resistant. The over-all effectiveness of the tin plate is not high until it is fused and a uniform thickness obtained. Passing through an induction-heating coil, however, as shown in Fig. 204, the granular surface is transformed into a smooth, mirror-like surface, as indicated at the right. The high-frequency-heating equipment operates at speeds up to 1,000 ft. per min., while gas furnaces are limited to approximately 150 ft. per min.

The usual rehandling problem is simplified, since sufficient power can be generated in the sheet to heat the strip to the fusion

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point of tin immediately after it passes through the plating tank. Within 0.7 sec. after the strip enters the heating coil, the temperature is brought up to 450°F., where the tin melts and starts to flow into an even surface. Only a few feet of line travel is required to produce sufficient heat, when the strip is passing through the heating coil at 1,000 ft. per min. Thus, the flowing operation becomes an integral part of the tinning line.

With the induction-heating method, the power input may be adjusted rapidly to accommodate changes in the speed of the
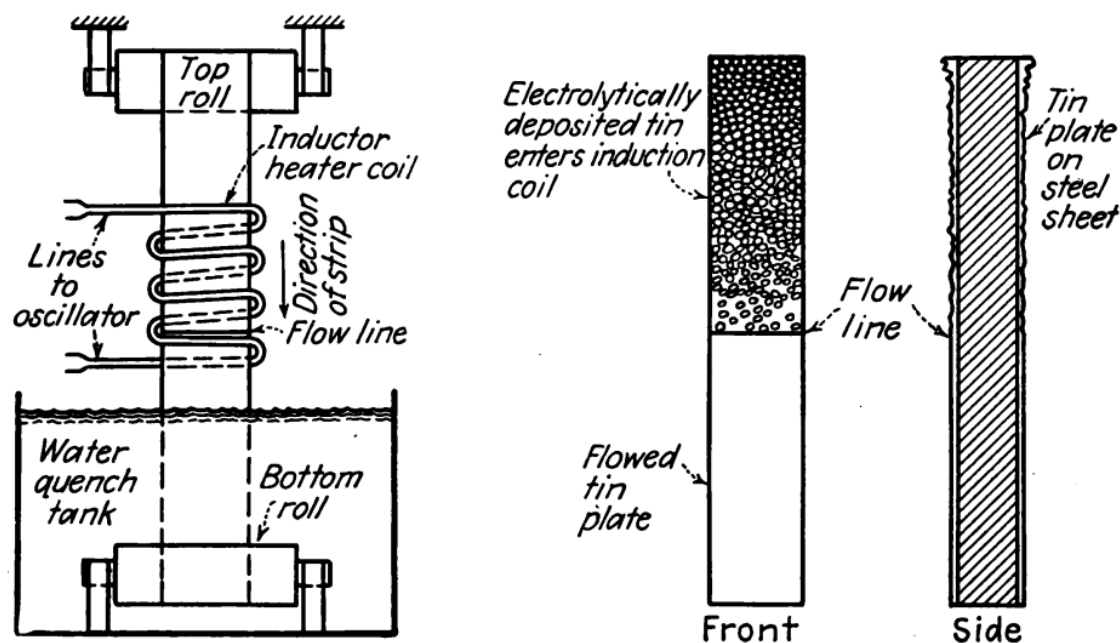
Fig. 204.—Constructional details of the heating coil used in connection with the flowing of tin plate. (*Courtesy of Westinghouse Elec. & Mfg. Co.*)

line, as during the periods of acceleration and deceleration when two coils are welded end to end. A speed change means merely a corresponding change in the power input to the induction-heater coil. The frequency at which the required current can be induced in the strip, without using abnormally high voltages, depends upon the thickness of the sheet. Since tin plate usually is 0.008 to 0.011 in. thick, a frequency of about 200,000 c.p.s. is most practical.

The induction-heating coil illustrated in Fig. 205 is rectangular in form, wound as close to the strip as mechanically possible. It acts as the primary of a transformer, while the strip itself constitutes a single-turn secondary. The induced current flows across the strip, paralleling the turns of the induction-heating

coil.   The heat generated in the strip is caused by the resistance of the strip to carry the current flowing through it.

Power from Oscillator Tubes.   The power is supplied by a vacuum-tube oscillator of 200 kw., somewhat similar to a radio-station transmitter.   Sixty-cycle alternating current is rectified to direct current, and then fed to the oscillator tubes where it is
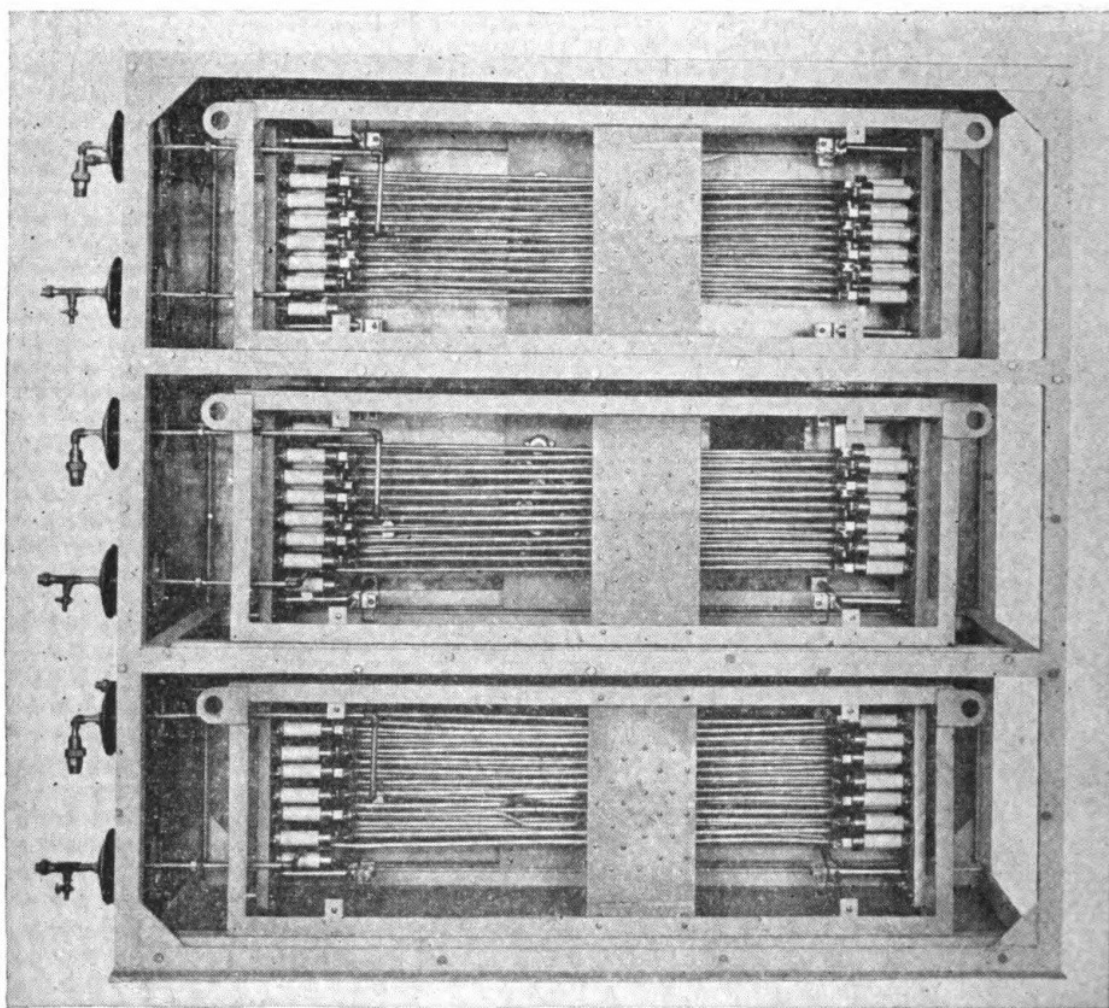
Fig. 205.—Rectangular-type induction-heating coil mounted by means of stand-off insulators, which is used for the heating of tinplate. (*Courtesy of Westinghouse Elec. & Mfg. Co.*)

converted to 200,000 c.p.s. and sent out through the induction-heating coil.   In Fig. 206 is shown a simplified schematic diagram of the circuit.

The several types of tinning lines thus far developed have two basic differences.   One difference lies in whether the speed through the plating bath is held constant or allowed to decrease when a fresh coil of steel is entered into the line; the other, in whether the plating tanks are vertical or horizontal.   In one type

of mill, the steel moves through the plating tanks at constant speed, and means are provided for accumulating enough slack at the entry end to allow the end of a new strip to be welded on. The other scheme, which usually makes possible a faster speed of strip, allows the entire line to slow down when necessary to start a new roll. In the line having horizontal plating tanks, the two sides of the sheet are tinned separately, allowing variation in thickness. In the vertical tank line, the sheet is tinned on both sides as one operation, and hence both sides are exactly alike.
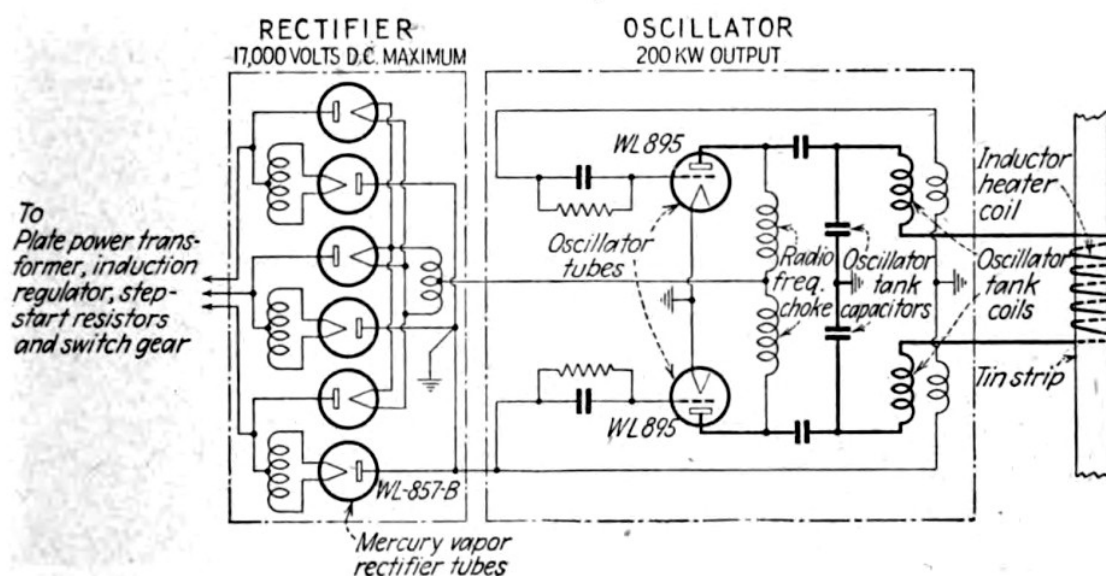
Fig. 206.—Diagrammatic layout of a 200-kw. output generator of the vacuum-tube type operating at 200 kc., as used for the continuous flowing of electrolytically deposited tin. (*Courtesy of Westinghouse Elec. & Mfg. Co.*)

Another feature of this induction-heating installation is an electric-eye control, which is focused on the fused tin as it passes the flow point in the induction-heating coil. The setting of the electric eye is adjusted to the mirrorlike finish of the tin and remains constant as long as there is no variation in the shiny surface. If, however, the proper flow failed to develop, as might happen through the failure of the high-frequency current, so that the dull gray surface appeared at this spot, then the electric eye, through a relay, would cause stoppage of the entire unit. An electric eye of this type is illustrated elsewhere in this chapter.

A general-purpose stand for hardening, annealing, drawing, and other processes where heat is required is illustrated in Fig. 207. At the left is shown a hardening station, which is provided

with a vertically operated work lift arranged so that the part can be raised into the induction coil if desired.   The piece shown
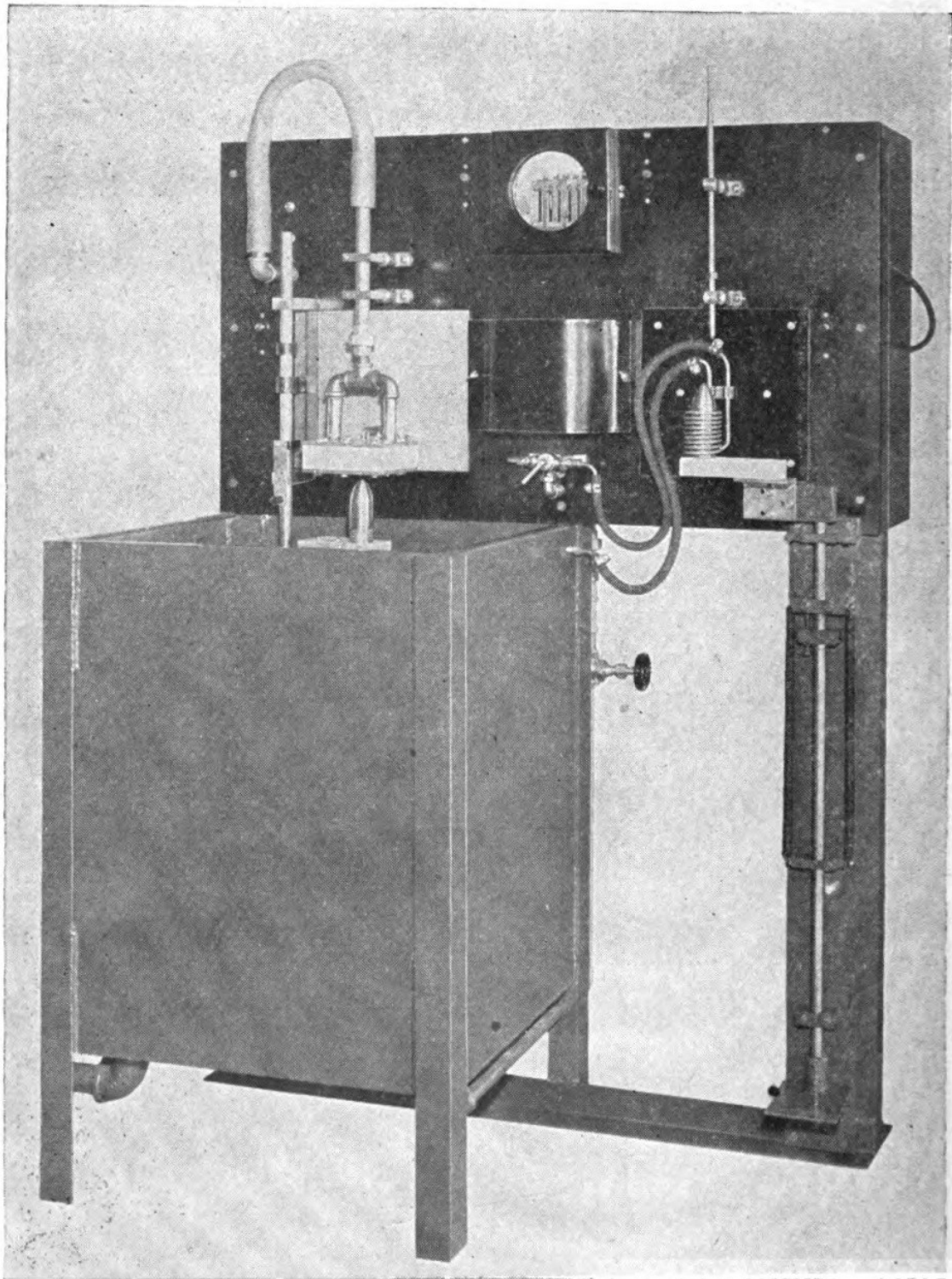
FIG. 207.—A two-station utility unit which is suited to miscellaneous hardening and heating operations.   Provision for spray or immersion quenching is available.   (*Courtesy of Ecco High Frequency Corp.*)

on the platform of this lift is a 37-mm. shell.   Directly above it is shown the spray-quench ring, while within the ring is located

the multiturn heating coil which is connected from the rear of the panel to the high-frequency generator.

In this heating station it also is possible to quench parts by immersion merely by lowering the work into the tank after it has been heated. Another feature of this quenching unit is a motor-driven pump, making it a self-contained hardening unit. This pump and reservoir make possible the use of either water or oil as a quenching medium. The coils and quench ring can be readily changed for different sizes of parts and the cycle, if
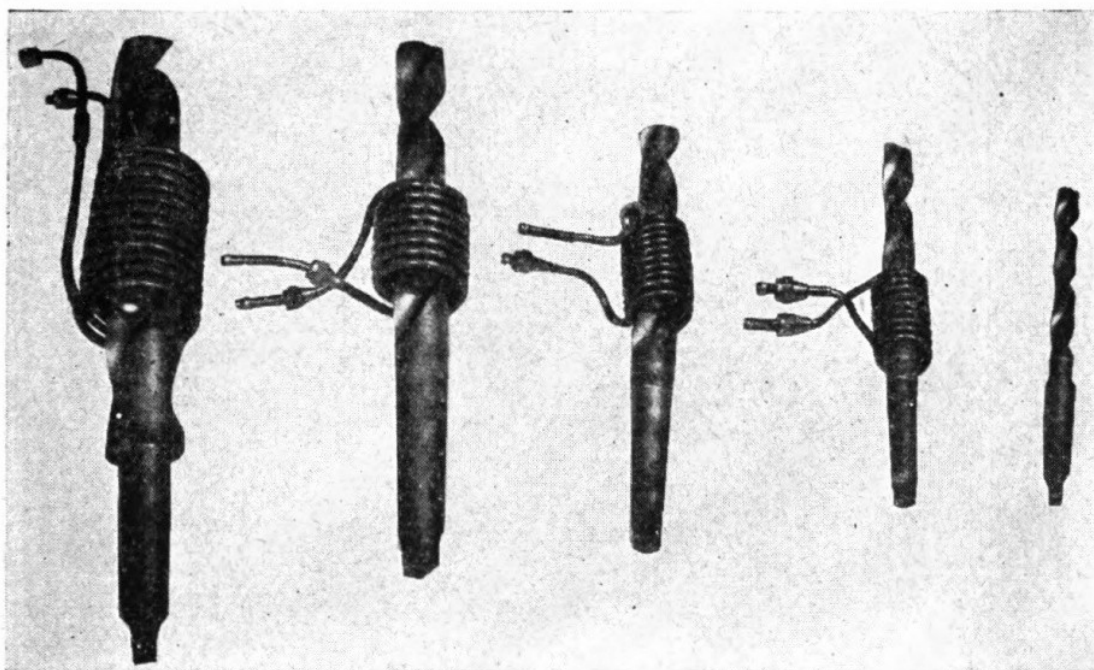
FIG. 208.—Induction heating can be applied in connection with straightening operations of shafts and other parts where localized heat is required, such as the twist drills shown above.

desired, is controlled automatically by means of the timer mounted at the upper part of the panel.

The station at the right is shown set up for annealing the end of the same shell. The work-holding platform is adjustable vertically and can be operated by the treadle shown at the lower right. Loading is done when the platform is at its lowest position, and then, by operating the treadle, the work is elevated into the heating coil to a predetermined height. A combination unit of this kind has a wide field of applications.

Among other uses for induction heat is that of straightening shafts, which might require a temperature of 900°F. or more to provide the correct amount of straightening effect. An operation of this kind can be carried out in various ways, one of which

would be to pass the part through a heating coil and generate heat to the section required, then shift the part between anvils so that the straightening ram can bear down against the heated area. Sometimes in the manufacture of large twist drills, which are made by welding a shank to the twist body, a straightening operation becomes necessary, and in Fig. 208 are illustrated several heating coils, together with the drills which they heat for straightening purposes. Here, the parts are heated to a tem-
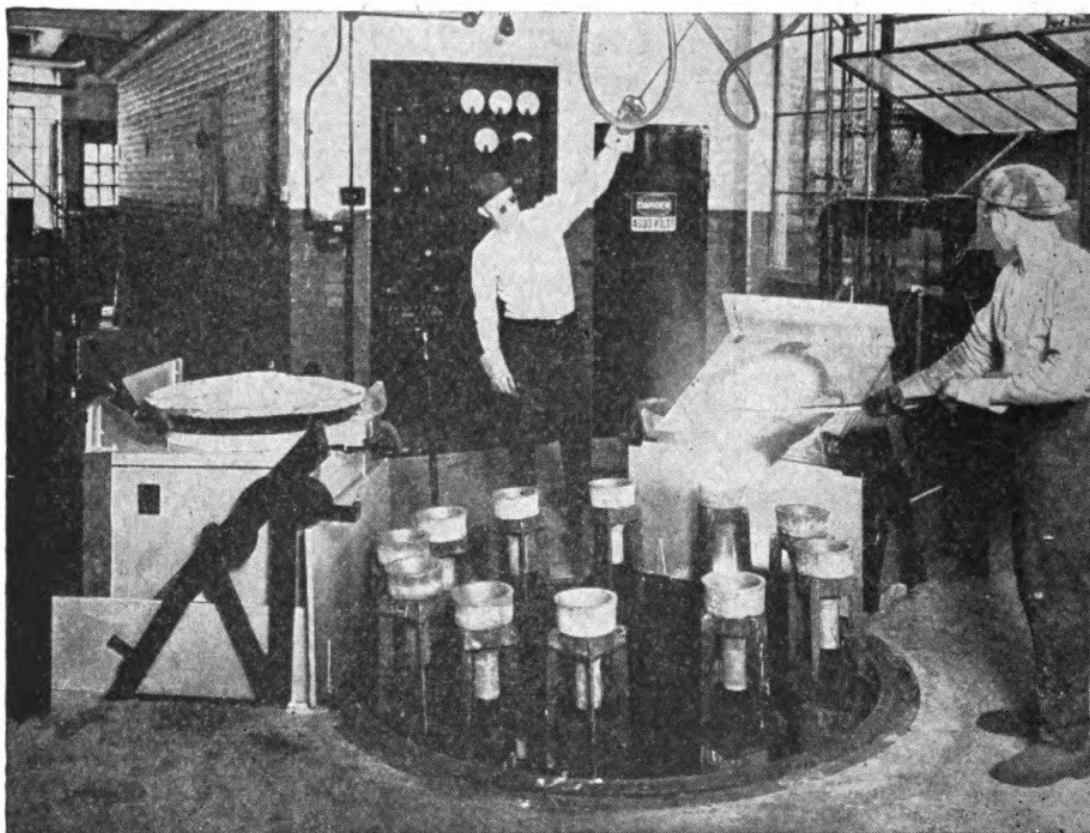
Fig. 209.—A well arranged induction-melting setup, using a turn-table and a series of containers for the molding of ingots. (*Courtesy of Hoskins Company, and Ajax Electrothermic Corp.*)

perature of 1300 to 1350°F., and then transferred to the straightening press, located close by.

The use of induction generators for the melting of metals can be arranged for the alternate operation of two furnaces, as shown in Fig. 209. In this case, each furnace has a capacity of 600 lb. of metal. The motor-generator set used for supplying the power is rated at 300 kw. and operates at a frequency of 960 c.p.s. The metal being melted is Chromel, and the time required for a charge is approximately 30 sec. The metal is poured in the form of ingots into containers, or molds arranged on a turntable,

so that after completion of the pouring of one ingot, the table is rotated to the correct position, bringing the next mold into pouring position.

Crucibles used for the induction melting of metals must be properly insulated and usually are set into a refractory lining, which separates them from the heating-coil assembly. A layer of mica sheet is placed on the inside of the coil and pressed tightly against it. Granular refractory then is placed at the bottom of the furnace and properly tamped in place, after which the crucible is properly positioned on it. Additional refractory then is tightly tamped between the mica and the crucible to within $\frac{1}{2}$ in. of the top. The remaining space is filled with an air-setting refractory cement to seal the granular refractory in place.

Crucibles for melting purposes are made in various styles and sizes and are available in either the conductive or nonconductive types. Where acid conditions prevail, crucibles made of bonded silica are used for steel melting. Magnesia crucibles are made of sintered magnesia and contain a percentage of bond, so that where basic conditions are desired they can be used for the melting of steel.

FIG. 210.—Induction-heating setup arranged with a vacuum-type furnace for the treating of tungsten-carbide powder. (*Courtesy of Ecco High Frequency Corp.*)

Zirconium silicated bonded crucibles are used for the melting of platinum, and clay graphite crucibles, which partially heat by induction, are used for copper, gold, and silver. Clay graphite crucibles, with a sufficient amount of silicon carbide, usually are

highly conductive and will heat by direct induction, thus making melting somewhat faster. Straight graphite crucibles also heat by direct induction and often are used for heating nonconducting materials, such as oxides. They are also used for high-temperature melting, at around 3000°F. or higher.

In Fig. 210 is illustrated a high-frequency-heated sintering furnace used in the manufacture of tungsten carbide powder. The powder to be heated is located within a ceramic container
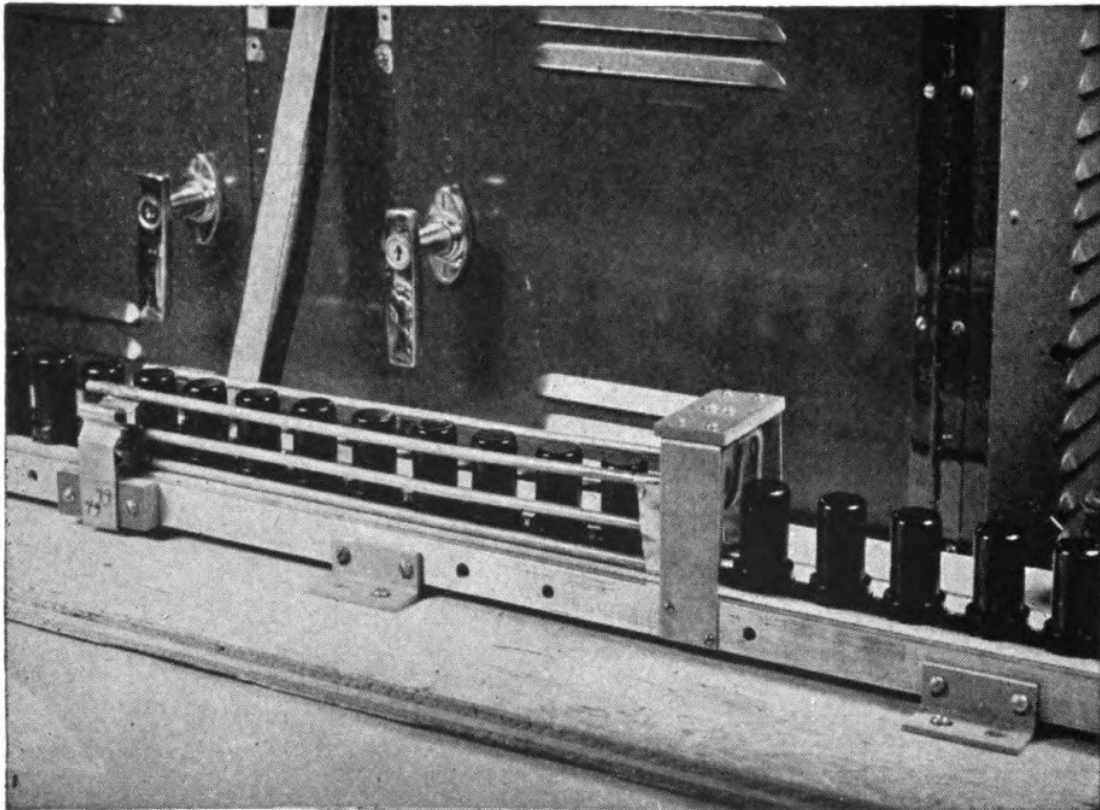
FIG. 211.—In this setup induction heating is used for the drying of paint. The metallic part is quickly heated as it is progressively fed through the inductor. (*Courtesy of Radio Corporation of America.*)

which is sealed, with a hydrogen atmosphere provided to eliminate the possible oxidation of the powder. High-frequency equipment is also used in the processing of other types of powdered metals.

Induction heating has many uses in connection with the drying of paint, especially on small metallic parts adaptable to rapid handling. After paint has been sprayed to a piece of metal, it is placed within a heating coil or fed past an inductor which dries the paint almost instantaneously, because of the heat inducted into the metal. With the induction process it has often been

noted that a better bond is provided and that there are fewer rejects.

In oven-baking paint to metal radio tubes, for example, the tubes are sprayed and normally require preheating for 5 min., then are placed in trays and baked for 45 min. As a contrast to this method, the induction-heating setup shown in Fig. 211 shows a continuous-conveyor process, using parallel-type inductors arranged so that as the work passes these coils, heat is induced into the metal shell, and the paint can be baked in as little as 15 sec. In this operation, using a 2-kw. generator, a production of 2,400 tubes per hour is possible.
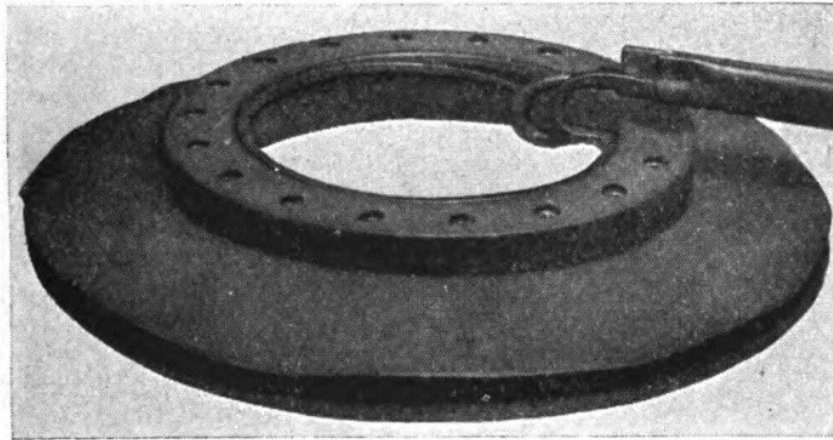
Fig. 212.—Induction-heating coils can be effectively used for the removing of bonded rubber from metal parts.

Somewhat different use of induction heat is the breaking of bonds between rubber and steel pieces molded together. In the many products in which rubber is used for various purposes, the rubber has to be removed after a certain amount of wear. When these parts are heated in a conduction-type furnace, the rubber acts as an insulator for the metal insert and high temperatures are necessary to apply to the bond sufficient heat to break it. Often the excess heat required injures the rubber. By means of induction heat, however, steel can be heated within the rubber almost instantaneously without affecting the rubber. By this process the bond is broken at temperatures of 300 to 600°F., so that the rubber can be reworked. Likewise, after sandblasting or cleaning, the metal insert, too, can be reused.

A representative setup of this kind is illustrated in Fig. 212. Here a molded rubber coating is being removed from a steel core. Heat is applied to the steel insert by means of a single-turn coil

$6\frac{1}{2}$ in. in diameter. The steel is brought up to a temperature of 550 to 600°F. in approximately 12 sec. The rubber immediately breaks loose at the bond and can readily be removed. The same process is used for the reclaiming of molded rubber on tank tracks.

A setup for drilling a small hole in a wooden block is illustrated in Fig. 213. Here a heating coil of the single-turn type is located directly over the end of the drill, which, of course, becomes heated. The drill is rotated and the wooden block is fed progressively, so that a combination burning and drilling action
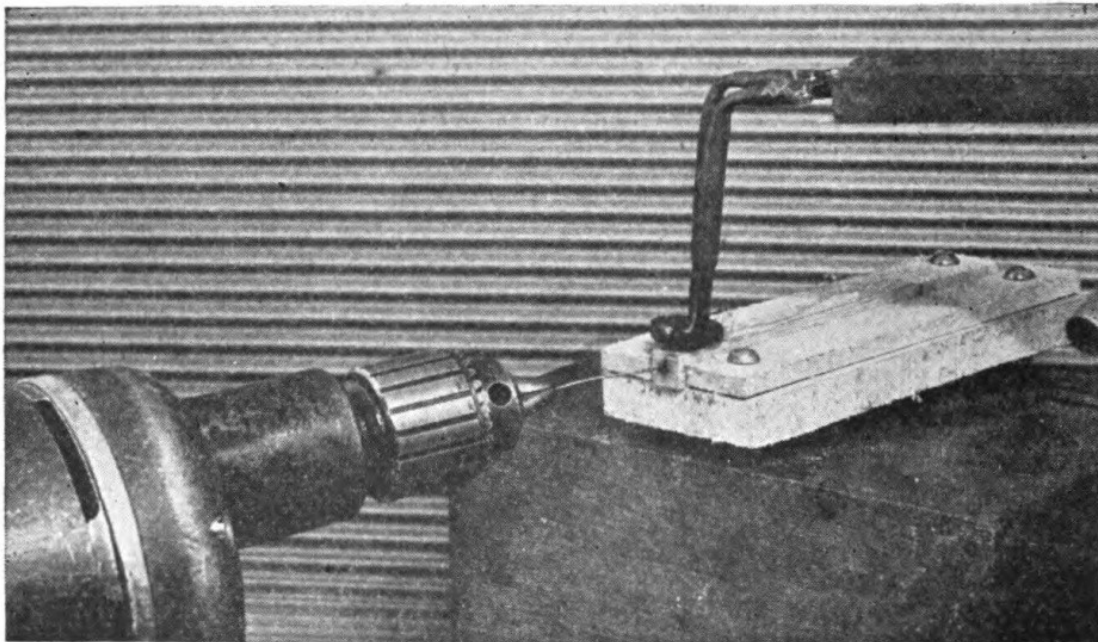
FIG. 213.—A setup which uses a small induction coil to heat a wire rod for drilling a small hole in wood.

results. The high-frequency current naturally passes through the wood, so that the end of the drill remains at constant temperature throughout the drilling operation.

Solenoids, electromagnets, and electrically operated trips can be used in many ways in induction-hardening operations. A setup showing the use of a solenoid in induction hardening is illustrated diagramatically in Fig. 214. The workpiece to be hardened is placed within the heating coil and rests on the plate *A*. After the heating cycle has been completed, the solenoid withdraws this plate and the work drops into the oil reservoir directly below. In applying trip mechanisms of this kind, it is well to use some form of support for the part being heated, such as a V block underneath the heating coil, so that the sliding action of the trip will not tend to move the work against the coil.

Of course the coil can be insulated, so that contact would have no effect.

The diagram in Fig. 215 shows another application of a solenoid valve for releasing parts to be quenched. Here the
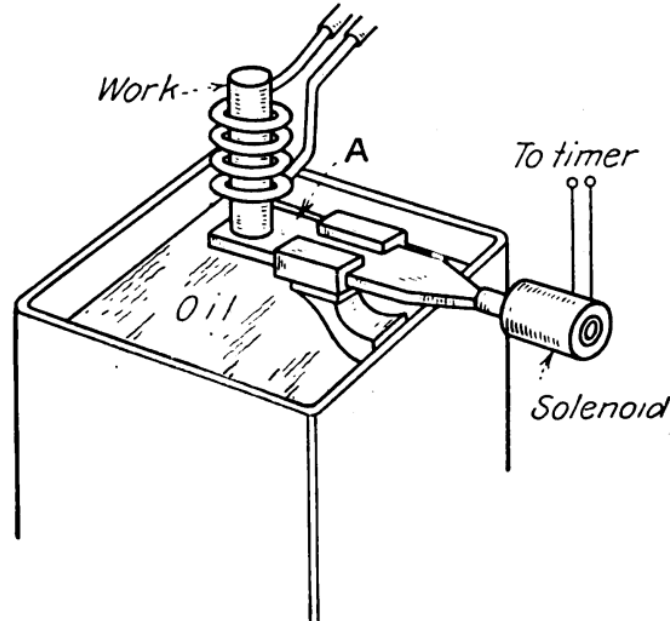
FIG. 214.—Solenoid-operated devices can be used in the hardening of parts which require submerged quenching.

work rests on hinged supports arranged to open automatically after the heat cycle has been completed, so that the part will drop directly into the quench bath below. The various cycles of the
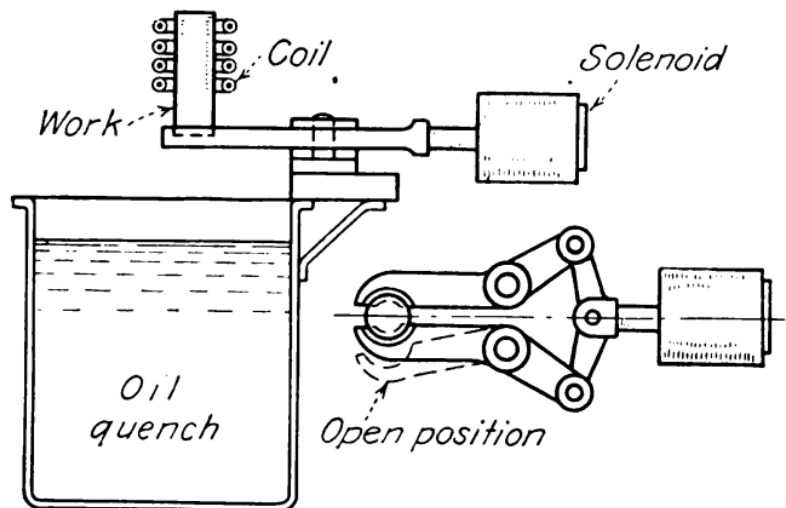
FIG. 215.—A solenoid-operated workholder, which automatically releases the work into an oil bath after heating.

operation are controlled by means of a multi-stage timer, so that the operator has only to place the piece of work within the coil and then engage a push-button station to begin the cycle.

Temperature is usually determined by eye, and as a rule close observations are possible. However, there are times when other means are required, and in Fig. 216 is shown a representative

FIG. 216.—Photoelectric units can be used in connection with timing devices for controlling heating temperatures.

use of a photoelectric eye for operating purposes in the hardening of a gear. The beam of the electric eye, which, of course, should include a photo tube sensitive to red, is focused on the surface

FIG. 217.—A diagram of a typical photoelectric circuit used for heat control. Various photo-cell circuits can be used for this purpose.

being heated. After attaining the correct temperature, the electric-eye unit cuts off the current from the heating coil by a relay and simultaneously applies the quench. This cycle

works in series with the multi-station timer used to control these functions.

A diagram of a suggested electrical circuit showing the photo tube is illustrated in Fig. 217. In this circuit the relay is energized by an increase in light on the photo tube. The circuit includes a direct-current power supply and responds to changes that take place in a fraction of a second. This type of control device can be applied to various heating operations and, of course, usually is limited to those in which the use of an electric eye would not be objectionable. Likewise, it is important that surrounding lights are not of too great intensity for the operation of the unit.
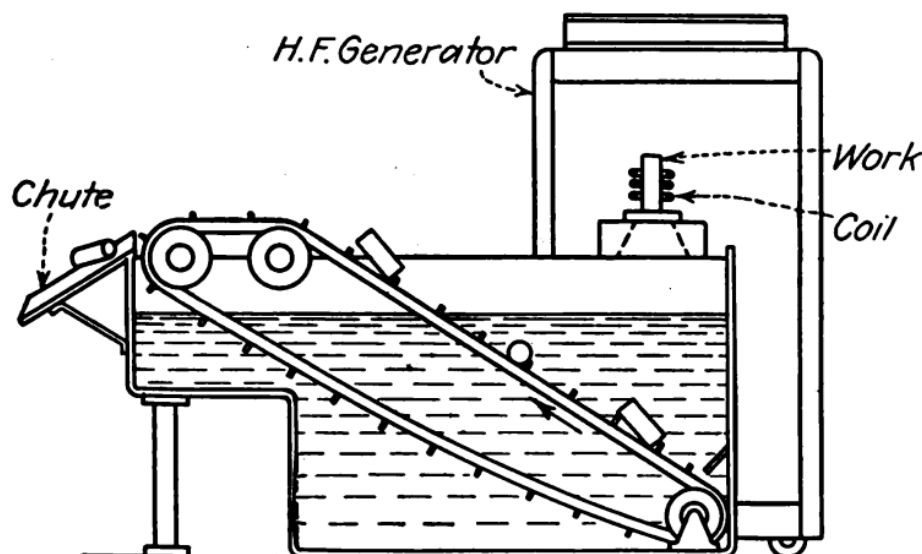
FIG. 218.—An oil bath arranged with a conveyor for removal of the parts after treatment.

When parts are submerged into an oil quench, it is possible to use a basket so that a stipulated quantity can be removed as required. This method usually is limited to small pieces, where several hundred parts can be removed at one time.

When the part becomes bulky, however, some means of removal by conveyor can be used, as illustrated in Fig. 218. The arrangement of the conveyor and the size of the reservoir will be determined entirely by the nature of the part. This is necessary in order to provide a suitable time duration in the quench bath. However, various combinations of conveyors can be employed so that the parts can be removed automatically, drained, and then passed on to some other conveyor, which carries them to subsequent operations.

Centrifugal Castings. High-frequency induction current is used for melting metals in small crucibles, in connection with centrifugally cast parts that are produced without the usual scale formation and to tolerances of ± 0.001 in. or even finer. In
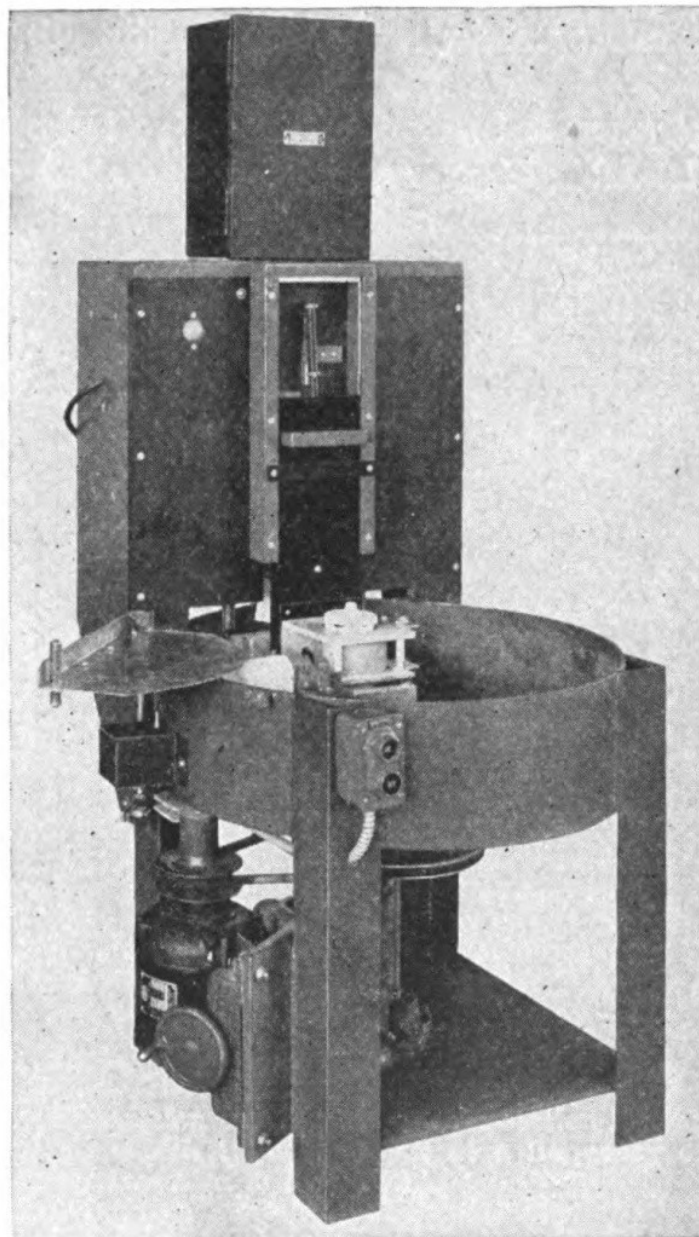
FIG. 219.—A centrifugal casting unit used in processing small precision parts, in which induction heating is used for the melting of small charges. (*Courtesy of Ecco High Frequency Corp.*)

brief, the process includes the making of a wax pattern or impression of the piece to be made; imbedding the wax pattern in a refractory material, such as an investant silica mold or ceramic molding compound, which then is thoroughly dried; heating the mold to a sufficient temperature for the wax to melt and run out,

leaving a cavity that carefully follows the original wax form; then mounting the mold in a centrifugal casting machine so arranged that the molten metal is injected into the mold cavities by centrifugal force as the mold assembly, including the crucible, rotates on an arm. This arm should have a radius of from 12 to 18 in. or more, according to the part and the material.

The metallic material to be cast usually is weighed, then placed in a small crucible around which an induction-heating coil is placed. With current applied, the metal is melted in a relatively short time, depending on its weight. The high-frequency current
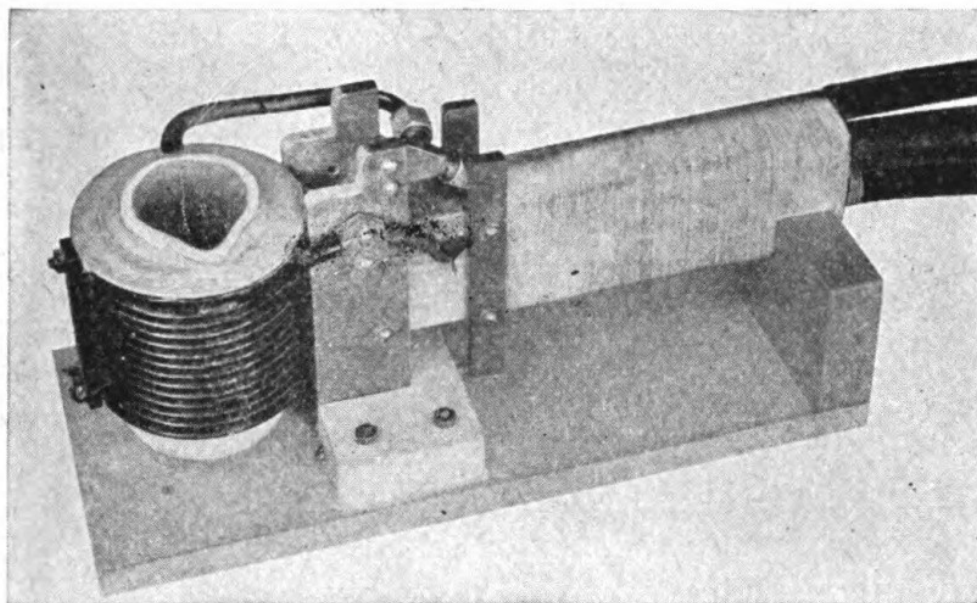
Fig. 220.—A high-frequency induction-heating ladle, provided with a hydrogen curtain, used in connection with the melting of small quantities of metal. (*Courtesy of Ecco High Frequency Corp.*)

passing through the charge has a tendency to cause agitation, so that complete mixing results, especially when different alloys are added to make up the charge.

A typical high-frequency casting machine for the making of small, intricate castings is illustrated in Fig. 219. The crucible, with its charge, is placed on the rotating arm, after which the heating coil is lowered over it. The generator is then energized and the metal in the crucible melted to its correct pouring temperature. The mold, however, which requires preheating, is not placed on the arm until the metal is almost ready for pouring. Usually the mold is heated in a separate oven, adjacent to the centrifugal casting machine. About 10 sec. before the melt is ready for pouring the panel light, shown at the upper

left, goes on, and the operator removes the preheated mold from the oven and places it on the arm of the centrifugal machine. A trip then is engaged, causing the heating coil to move upward, away from the crucible, and at the same time starting rotation of the arm. The crucible moves into proper position in relation to the mold and the molten metal fills the cavity of the mold by centrifugal action.

Centrifugal casting is limited to small parts, usually under 4 or 5 lb. weight. Practically any type of metal can be poured, however, including magnet steel, stainless alloys, Stellite and tool steels, as well as various nonferrous materials. The process is used only for the casting of intricate parts that normally require many machining operations. A charge weighing 1 lb. can be melted in 1 min., or slightly less, with a 20-kw. generator. Charges of 2 to 3 lb. require from 3 to 4 min.

Other induction-heating methods are applied to centrifugal casting. One of these uses a heating furnace of the ladle type, as illustrated in Fig. 220. In this method a series of flasks are placed in the centrifugal machine and preheated as required, then while the flasks are rotating the molten metal is poured into a distributor. This ladle-type furnace is made with provision for maintaining a hydrogen curtain above the melt in order to reduce the possibility of oxidation with such metals as may require this precaution. The hydrogen is fed through the tubing shown at upper left, so that the flame it produces covers the molten charge.

CHAPTER VIII

DESIGNING FOR INDUCTION HEATING

High-frequency induction heating for hardening, brazing, and soldering is having a marked effect on manufacturing methods and as time goes on will have a decided influence on the constructional design of many products. While in many cases design changes will be limited, there are examples of certain modifications which will make the adoption of induction heating more practical. These changes usually are not drastic, but more on the order of improvements to suit the characteristics of this method of heating.

All in all, it is largely a case of acquiring the technique of induction-heating requirements and then considering these needs to make its use successful. A sound general knowledge of what induction heating can and cannot do, though relatively simple, is basic to its practical application.

In checking cases where induction heating has not produced exactly what was wanted or expected, the cause usually could be traced to some design feature or details which could easily have been modified when the design was started. Thus it is evident that knowing from the beginning what is required to make induction heating successful may help to develop its full possibilities.

Induction heating provides the means of heating parts locally and heating them fast, whether in hardening or brazing. The only difficulty, generally speaking, lies in making a heating coil or inductor to surround or fit the surface of the part requiring heat, and to have a high-frequency generator with sufficient output power to heat the surface or surfaces adequately. With this, of course, a comprehensive knowledge of the formation of the heat pattern on the adjacent surfaces is advisable.

Induction-heating coils can be multiturn, as shown at *A*, Fig. 221, or single-turn as at *B*. From these two types any number of shapes and styles can be arranged to heat outside, inside, flat,

and irregular surfaces.   The magnetic lines of force surrounding
a coil, as at C, theoretically are equal in all directions from the
center line of the coil.   Their density outside the coil is less than
inside and, likewise, their density varies inversely as the distance
between the part to be heated and the coil is increased.   The
nearer the work to the coil, the faster will heat be generated to
the work's surface and vice versa.
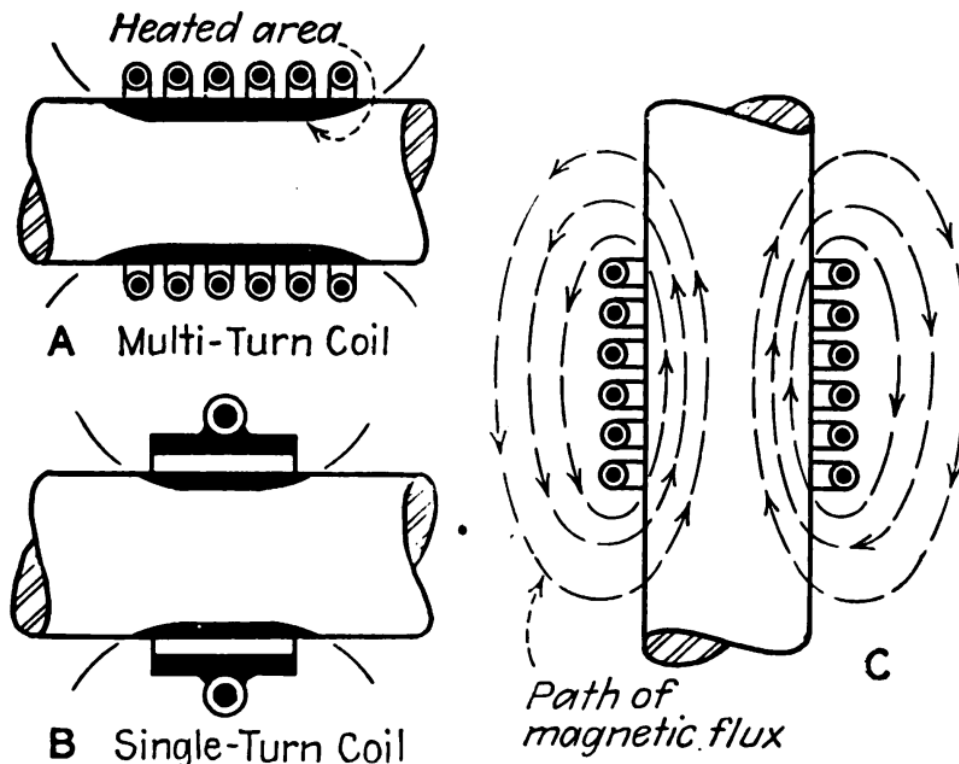
FIG. 221.—Most induction-heating coils are made of either one or several
turns of copper in the form of tubing or flat strip.   From these two types it is
possible to provide a wide variety of shapes and sizes to suit different heating
requirements.

When induction heating the surface of a shaft adjacent to a
shoulder, as illustrated in Fig. 222 at A, it is difficult to obtain
heat in the fillet or corner, since some of the flux energy from
the end of the induction coil will flow into the face of the flange,
as indicated at B.   This condition results in a "cold spot" at
the fillet, which can be heated only by conduction and which,
of course, would require added time in the heating cycle.   This
added time might also result in excessive heating at other por-
tions of the work, so that a modification of the design might
be the solution.   By adding a relief, as at C, the condition is
improved, or if a slight shoulder is desired, such as may be needed
for needle bearings, the design at D can be substituted.   In this

case the heat can be obtained in the sharp corner, the shoulder being comparatively light.

Another consideration in induction heating is that thin surfaces are liable to become overheated in relation to adjoining heavier sections. Where possible, therefore, uniform areas
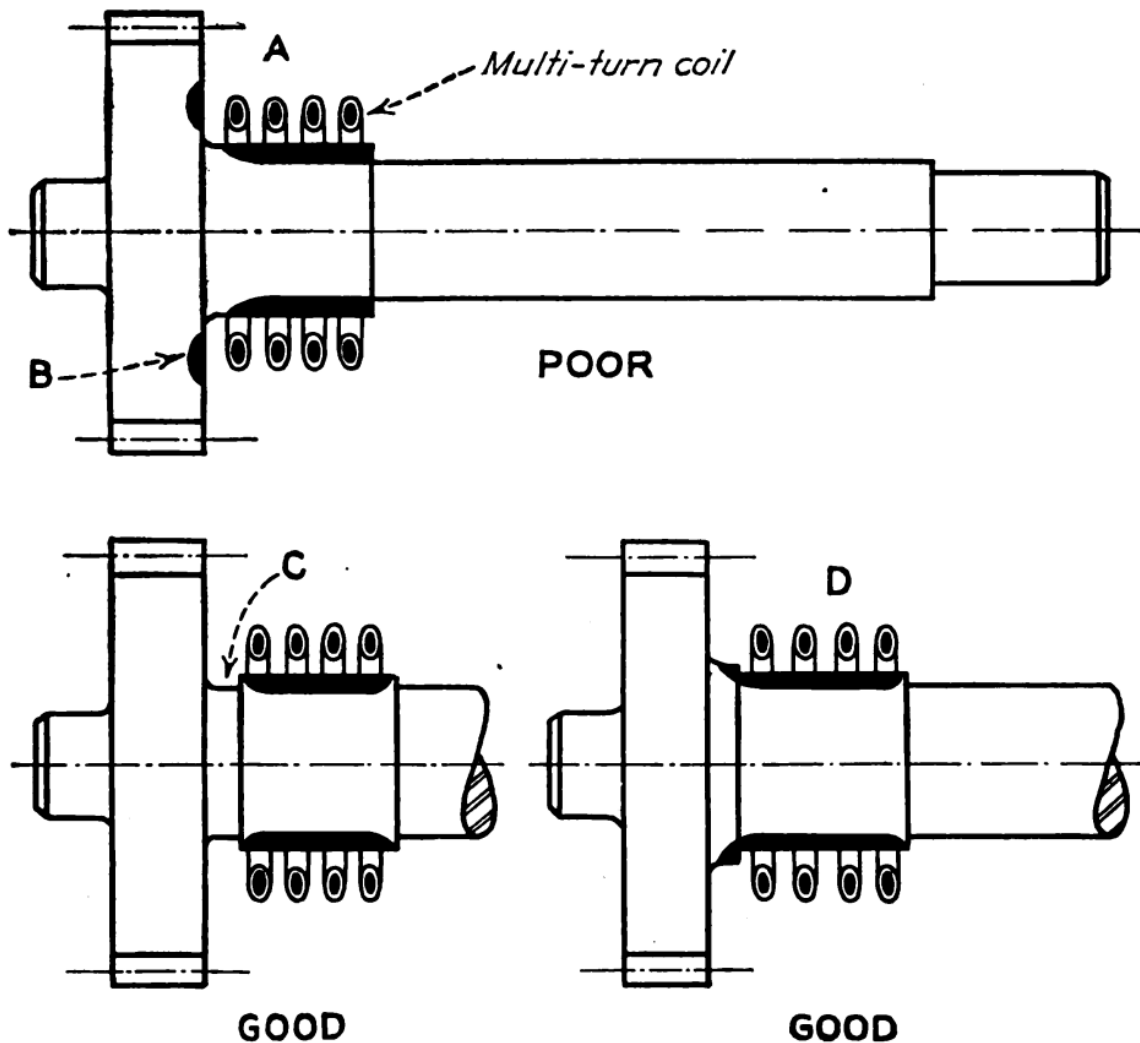
FIG. 222.—When a shaft made with a shoulder is heated, some of the flux density from the coil flows into the face of the flange and, as a rule, some modifications in design are required to assure heating the corner or fillet.

should be provided in the design of a part, to make heating more even. The end of the shaft at *A*, Fig. 223, for example, requiring hardening on the internal hole, would result in the generation of excessive heat through the thin section before the remainder of the hole reached the proper quenching temperature. By adding more metal between the hole and the bottom of the keyway, as at *B*, a more uniform heat will result and the danger of burning is overcome.

Sometimes this condition can be corrected by applying a copper plate in the keyway during the heating operation, so that the high-frequency current does not have to crowd through the thin area of the work only; but usually a modified design is to be preferred. Sometimes other forms of copper shields are used to cut off heat at limited areas, but these usually are applied on existing parts which were not designed for induction heating. Sharp corners, too, are liable to result in some overheating,
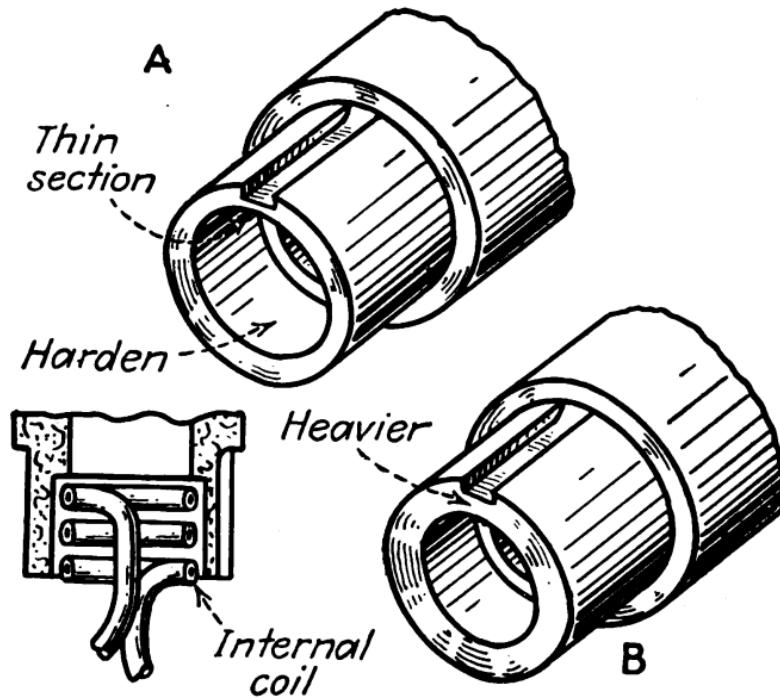
FIG. 223.—In designing parts to be inductively heated it is well to avoid thin sections, which are likely to become overheated due to the crowding of the flux through a restricted area.

sometimes referred to as "edge effect." Here, again, by modification in design and a knowledge of induction-heating requirements, such difficulties can be easily overcome.

Since localized surfaces can be inductively hardened without heating adjoining areas, the application of induction heating is going to result in new designing techniques. In some cases improved products will be made available, in others it will be possible to obtain results that ordinarily would be impossible or too difficult to consider by other means. Manufacturing processes will also be simplified. For example, carburizing by substituting higher carbon steels will be eliminated, while parts from two or more sections will be fabricated instead of a one-piece design which might necessitate difficult machining setups.
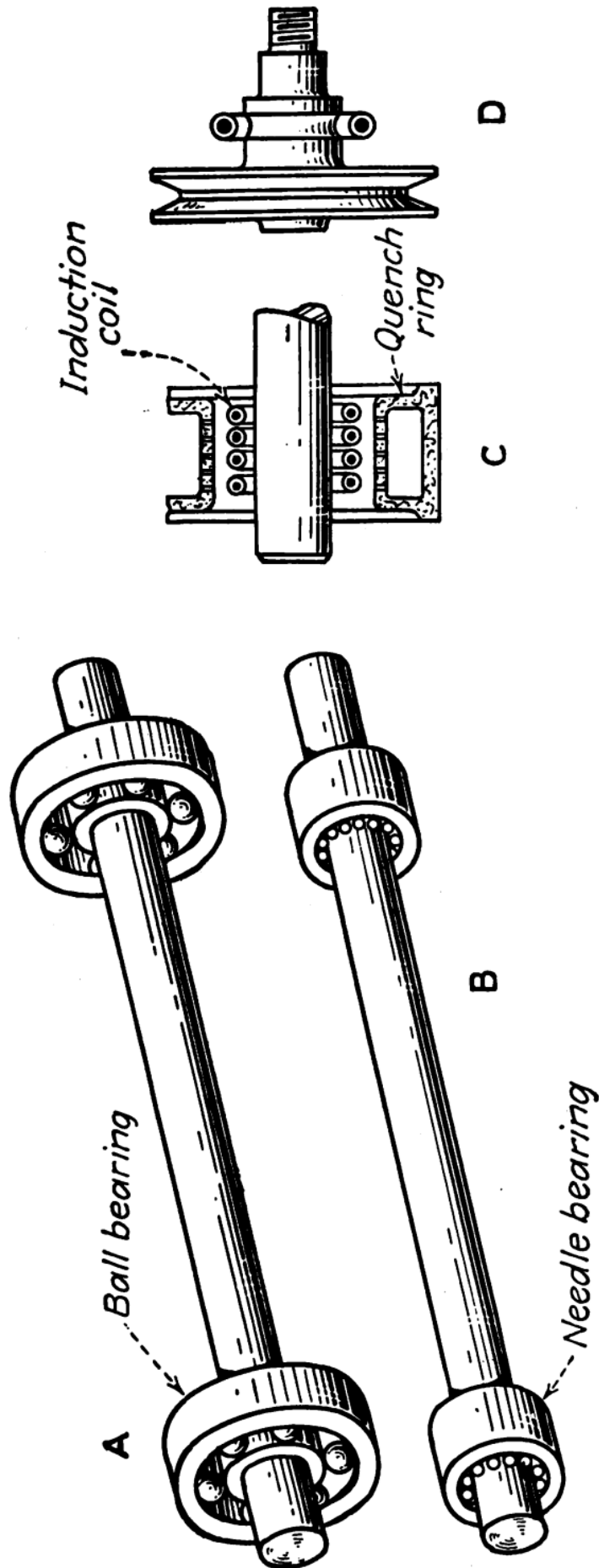
FIG. 224.—Roller bearings can be applied to long shafts by localized hardening the surfaces on which the bearings operate. This procedure eliminates the necessity of heating the entire shaft and also prevents distortion.

In the design of a machine shaft to operate in anti-friction bearings, where space was a limiting factor, a change from ball bearings to needle bearings was desired. The former design, shown at *A* in Fig. 224, could not be used, due to a parallel shaft operating on close centers. Substituting the design shown at *B*, it was possible to harden the bearing surfaces selectively, using the heating coil and quench ring illustrated at *C*. The shaft, made of 0.50 carbon steel, is hardened to 62 to 64 Rockwell C, suitable for a needle-bearing race, and since heating is localized the usual straightening and cleaning operations ordinarily required have been eliminated. This same means of induction
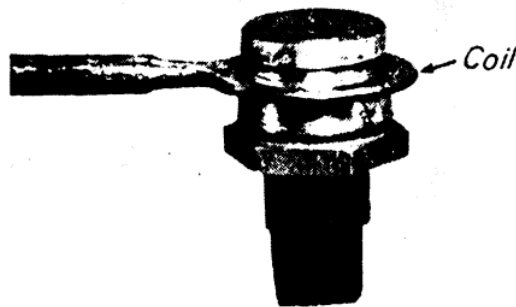
FIG. 225.—Localized bearings can be inductively hardened, such as the integral ball race shown above. The formation of scale and the possibility of distortion are usually overcome.

hardening can be applied to races for ball bearings, as shown at *D*, thus eliminating difficulties that might arise through heating of such a part.

An example of a part in which the inner ball race is made integral with one end is illustrated in Fig. 225. As will be seen, a single-turn induction coil is arranged to surround the groove. With this coil energized, heating of the part will be localized to the ball race. The depth of penetration and the area heated can be controlled by the time cycle. After quench, the ball race will be exceptionally hard and, since heating was localized to so small an area, the balance of the part remains metallurgically unchanged, and warping or deformation cannot take place.

Through induction heat it is possible to obtain different hardnesses not ordinarily obtainable on a single piece. An example of this is the gear illustrated in Fig. 226, on which three separate induction-heating operations are performed. The cam surface is hardened to 60 to 62 Rockwell C, maximum resistance to

wear being desired. The gear teeth are hardened to 53 to 55 Rockwell C for their normal service, whereas the clutch teeth are hardened to 48 to 50 Rockwell C, to resist wear and withstand shock without fracture. Such modifications in hardnesses are obtained by slight variations in heating and quenching cycles, which automatically are timed so that uniformity is maintained.

The sprocket shown in Fig. 227 represents an example of modified design which through induction hardening has resulted in manufacturing economies. Formerly this sprocket was
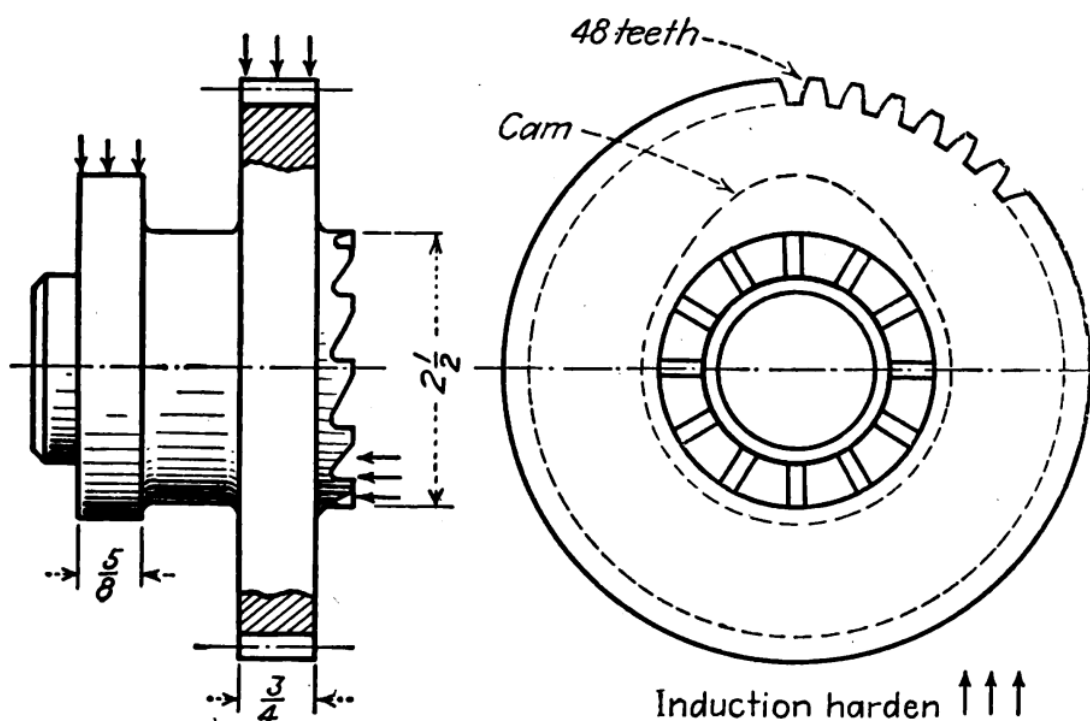
Fig. 226.—Induction heating permits the hardening of various surfaces of a single piece to different degrees of hardness, which ordinarily would be difficult to accomplish by other means of heat treatment.

carburized and required rough-machining, copperplating, remachining to remove copperplate, cutting of teeth, carburizing, hardening, chucking from pitch of teeth to grind hole, and assembling of bushing. By using a higher carbon steel, the new processing requires only machining of blank, assembly of bushing, cutting of teeth, and induction hardening of teeth. Since the teeth are cut after assembly of the bushing, concentricity is assured and more easily obtained than by the former method. At the right is shown a portion of the inductor formed to suit the contour of the teeth so that a uniform heat pattern is obtained with no excessive heat at the top of the teeth, as might happen with a flat or copper-tube coil. The elimination of carburizing,

as in this example, has a broad field of application and shows the advisability of considering induction heating in the design of mechanical parts.
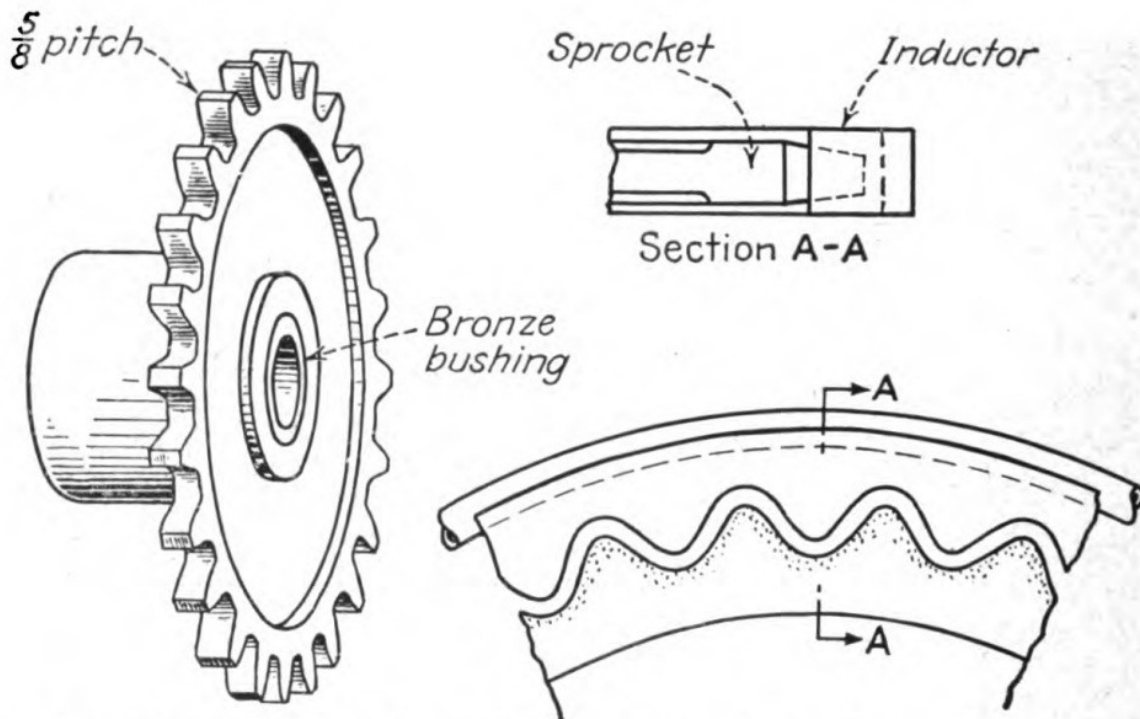
FIG. 227.—By substituting a higher carbon steel for this sprocket, various economies have been gained, especially the elimination of carburizing and several machining operations.

As a matter of safety it is good practice, when changing from a through-hardened part to one on which only local surfaces are induction hardened, or from an alloy steel to a plain carbon steel, to add some thickness or size to certain sections. The slight amount of metal added does not usually alter material cost.
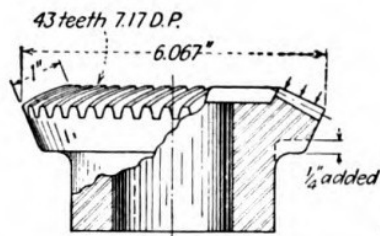
FIG. 228.—When substituting surface hardening for through hardening, it may be advisable to increase the area of certain sections as a matter of safety.

A typical example of such a change is the spiral bevel gear illustrated in Fig. 228. Formerly made of S.A.E. 4615 carburized, hardened, and lapped, it is now made of C-1141, induction hardened, and lapped. Lapping is done in far less time than before, since less distortion and absolutely no scale are produced, while equal hardness is obtained. After adding about ¼ in. to the back face of the gear for extra strength, from a standpoint of trueness and other operating qualities it is better than before, besides cost-

ing less in both material and labor. The heat-treating cycle for this bevel gear includes an induction-heating period of about 25 sec., followed by water-jet quenching of 15 sec.

A design change brought about by induction heating is the flanged shaft shown in Fig. 229, formerly made from the forging *A*, and requiring machining of the flange profile as an integral member, as at *B*. At *C* is shown the two-piece design, the flange being a stamping brazed to the shaft. The single-turn inductor,

FORGING   **FINISHED PIECE**   **REDESIGN**
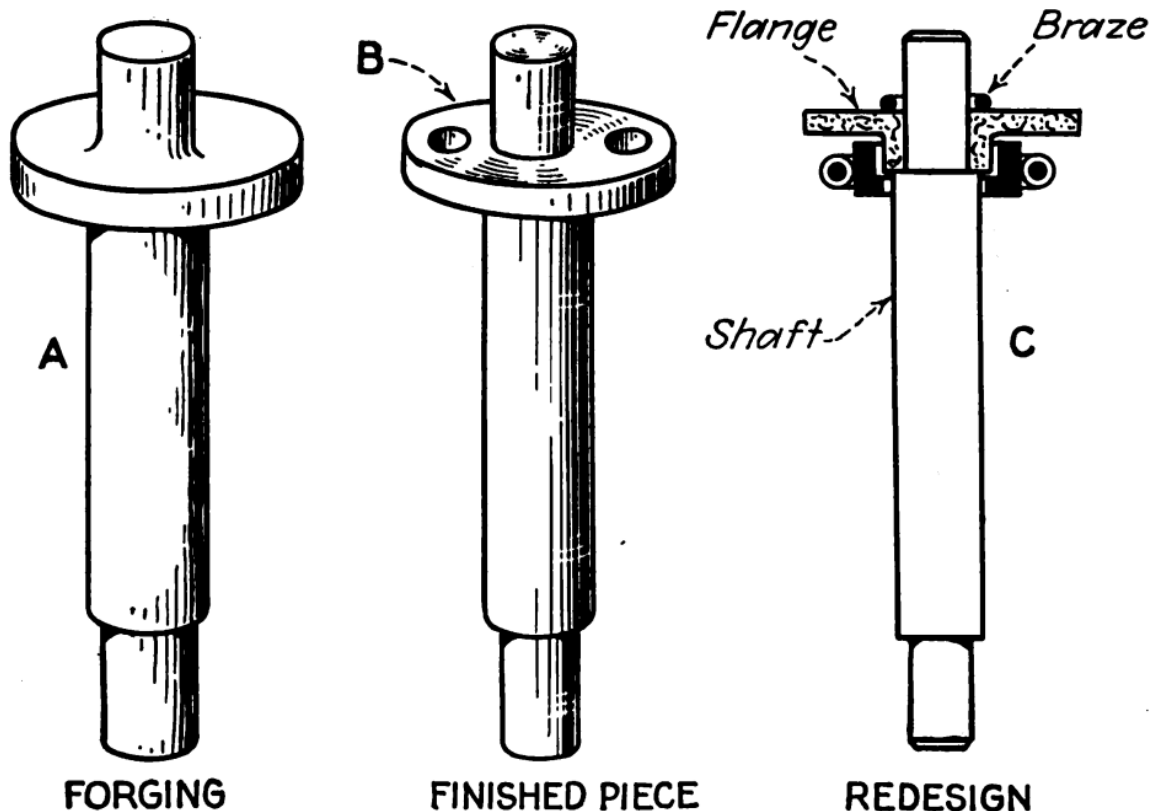
FIG. 229.—An example of a design change made possible by induction heating, in which a flange is brazed to a shaft instead of being cut integrally from a solid piece.

used for alloy brazing, is shown in its relative position during the joining operation. A ring of alloy is placed at the joint, as shown, and with only a few seconds of heat a smooth, perfect joint is attained.

A part which utilizes induction heating for brazing and hardening is illustrated in Fig. 230. Here a large gear is assembled onto a shaft, and then induction brazed with the heating coil, as shown. The small gear, of course, is made integral with the shaft. This part formerly was made in one piece, but now is made of two separate parts, which shows the possible scope of induction heating in relation to product design.

In processing this part, the larger gear is machined and brazed to the shaft, then after assembly the gear teeth are shaved. This operation provides for the correction of any misalignment and assures concentricity with the smaller gear.
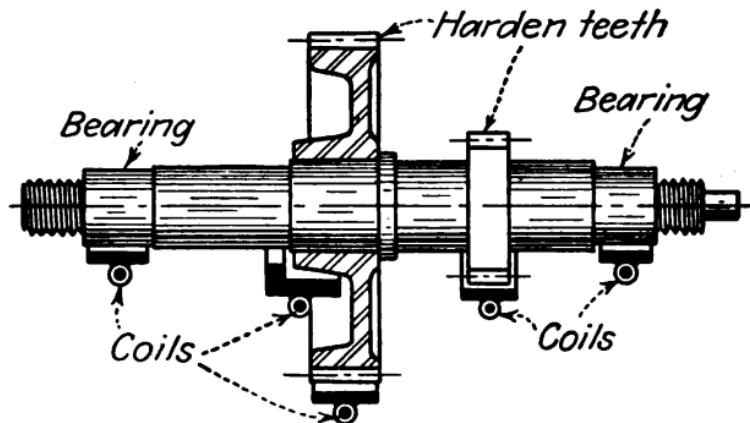
Fig. 230.—Induction heating as a means of combined brazing and hardening will permit the construction of fabricated assemblies to substitute for forgings, so that manufacturing economies can be attained.

Both sets of gear teeth are hardened by means of the coils indicated. On this same part there also are two journals to be hardened, one at each end of the shaft, onto which roller-bearing assemblies are attached, so that the hardened areas of the shafts become the inner bearing surfaces.

Design for induction brazing requires some consideration, yet in many cases joints of a wide range can be handled effectively
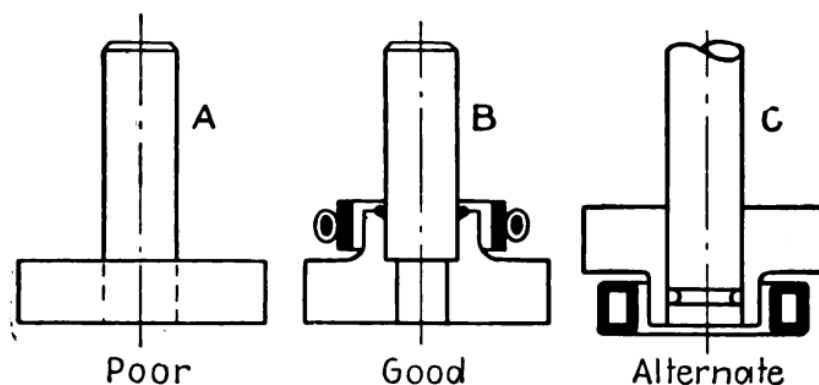
Fig. 231.—When joining parts together by means of induction brazing, it is well to consider the size and shape of the parts, so that correct heat distribution can be obtained.

without modification. The basic consideration is to analyze the parts to be joined to determine if more heat is needed at one section than another, and then design the heating coil to suit the application. Occasionally on light sections it is better to allow

the heat to flow by conduction from a heavier section, which, of course, is determined by mass and size. However, with some parts the shape may need modifying. For example, the joint at *A* in Fig. 231 is not particularly suited to induction brazing since the entire flange would have to be heated in order to assure heat reaching the joint. By providing a hub, as at *B*, a simple one-turn coil can be used and heat applied quickly to the joint without affecting the outer portion of the flange. The modified design *C* is also practical. Here a preformed ring of brazing alloy is placed in a groove cut in the shaft prior to assembling the two pieces. Here again, a single-turn inductor will generate heat to the local surfaces to be joined.
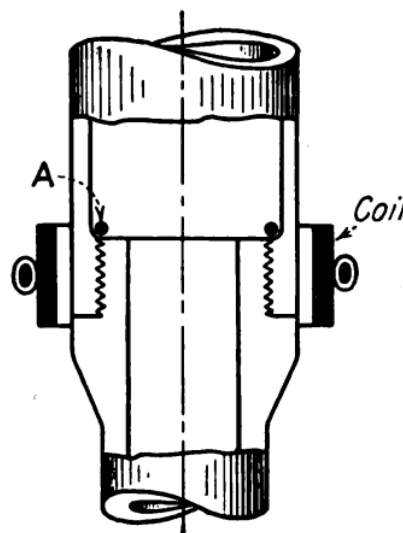
FIG. 232.—When two sections requiring torsional strength are to be brazed together it is possible to spline both sections.

When a high-pressure brazed joint is required, it is possible to thread the members to be joined, then assemble them as shown in Fig. 232. A ring of silver alloy *A* is placed inside the assembly as shown. The heating coil is arranged
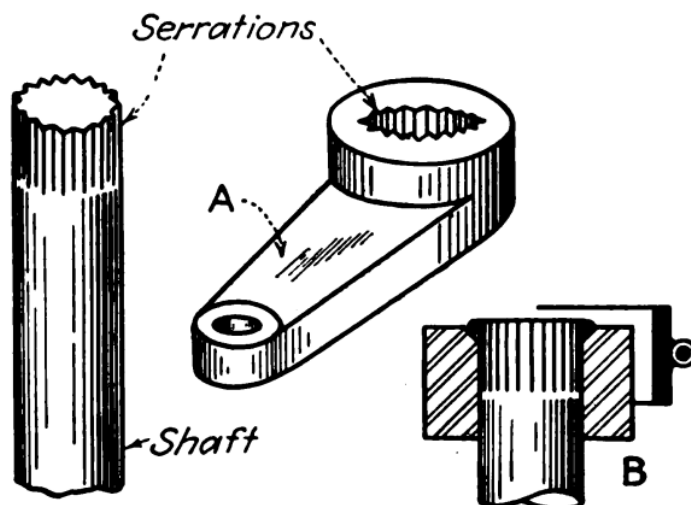
FIG. 233.—An exceptionally strong joint can be produced by the method shown, which includes a threaded assembly that is silver brazed. A joint of this type will have exceptional strength and withstand high pressures.

to generate heat from the outside in, and when the brazing material flows it will run through the threaded area and form an exceptionally strong bond.

There are many other ways to make high-pressure joints, as well as joints which must overcome torsional strains. Some of these would include keyways, multisplines, serrations, pins, and various forms of threaded assemblies.

A form of brazed joint which can be used when torsional strains must be overcome is illustrated in Fig. 233. The end of the shaft is provided with serrations to match the broached serrations in the hole of the arm *A*. When brazing alloy is applied to the joint, it flows throughout the serrations and forms an exceptionally strong bond. At *B* is illustrated a section through the

BAD   GOOD
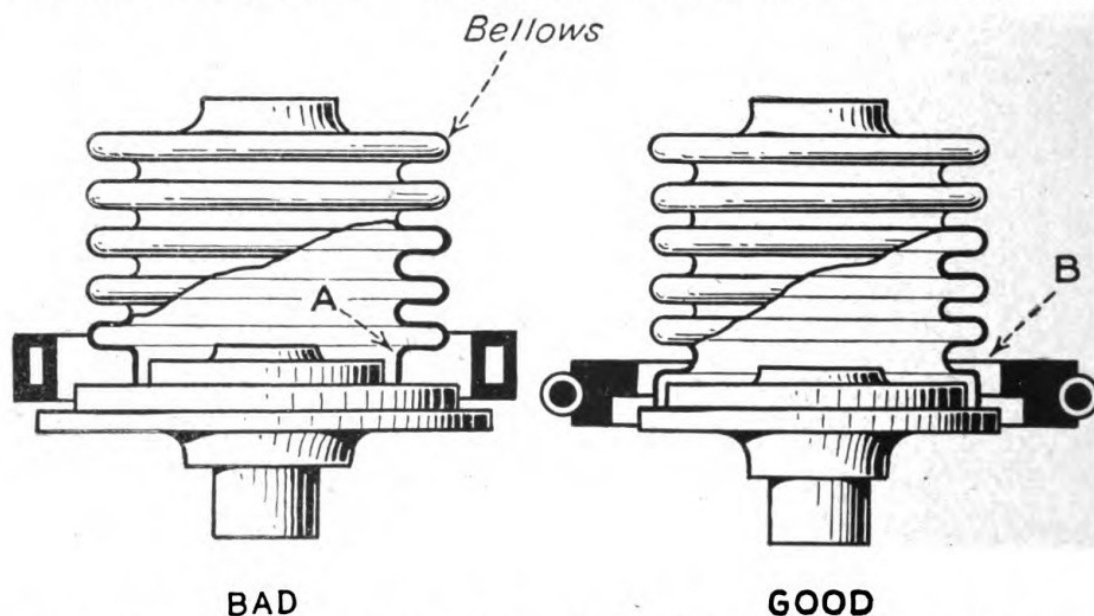
FIG. 234.—Sometimes a very slight modification in design will make an otherwise impossible joint suitable for induction heating. The bellows assembly shown above is an example. The design at the left is impractical, whereas the modified construction at the right is excellent.

assembly, showing the relation of the induction coil and the ring of brazing alloy.

Another design change necessary for joining by induction heat is the bellows shown in Fig. 234. With the design at *A* the coupling from the coil to the surface requiring soldering is too great, resulting in heat dissipation to the outer surfaces only. By revising the design so that the joint is at the outside edge, as at *B*, heat can be precisely applied to the desired surface. Such modifications create no difficulties when designs are originated, but clearly show why a knowledge of induction-heating technique is desirable.

Another example of a two-piece design requiring brazing and hardening is the bevel gear illustrated in Fig. 235. The teeth

of the gear would be difficult to cut as an integral member of the spindle. Likewise, since the gear teeth must be hard, any form of brazing after hardening might cause annealing or drawing. By the induction-heating method, the brazing of the two parts is done by an internal coil, as shown at *A*, fo lowed by hardening of the teeth, as at *B*, using a multiturn coil which limits heat to the teeth. A spray quench follows the heating portion of the
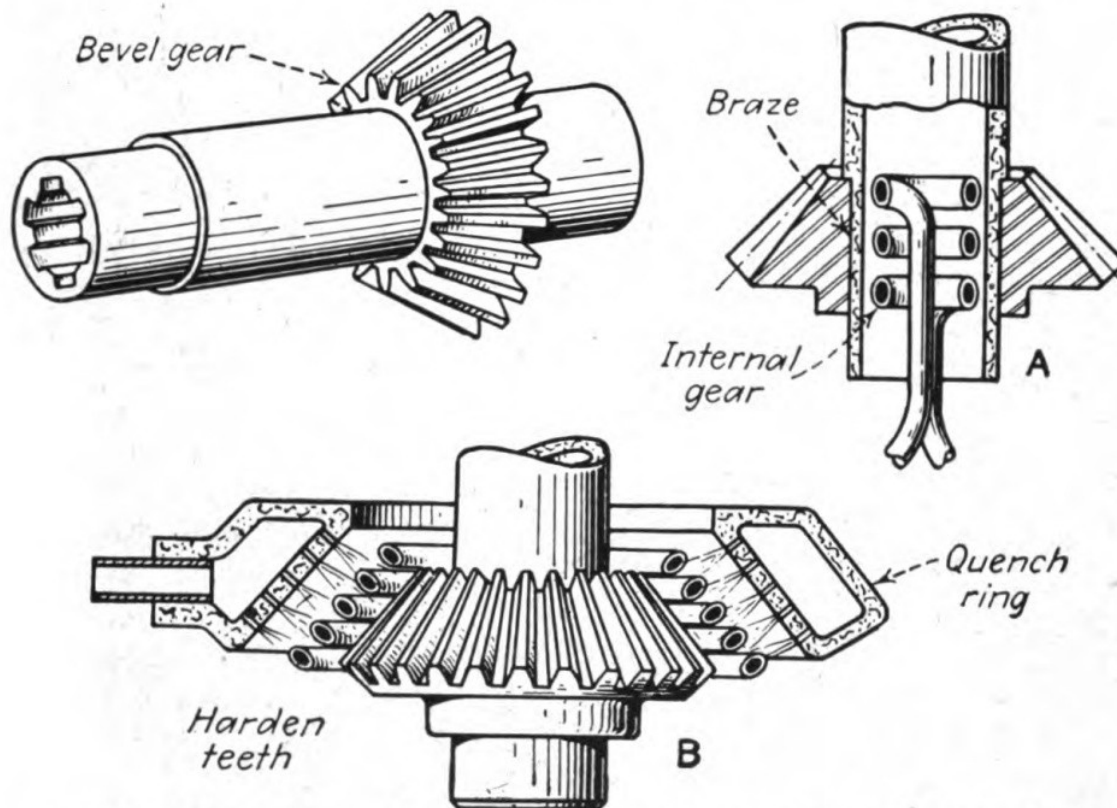
Fig. 235.—This illustration shows the application of induction heating for the brazing of a beveled gear to a shaft, as well as the hardening of the teeth after assembly. A part of this type would present manufacturing difficulties by other means of processing.

cycle, and the entire hardening operation is completed at a rate of three pieces per minute.

The part illustrated at *A*, Fig. 236, is a clutch shaft made in one piece, while at *B* is shown the design made from two pieces. Induction brazing is by means of the single-turn coil *C*, whereas hardening of the clutch teeth is by means of the pancake coil *D*. Inasmuch as the heat required for hardening the teeth is strictly localized, there is no danger of the previously brazed joint's being reheated.

In Fig. 237 is shown an excellent example of induction harden-ing where former manufacturing difficulties have been overcome.

The part represents a long spline shaft made of a 0.50 carbon steel heat-treated to a hardness of 30 to 32 Rockwell C prior to final machining. On each end of the short spline are required
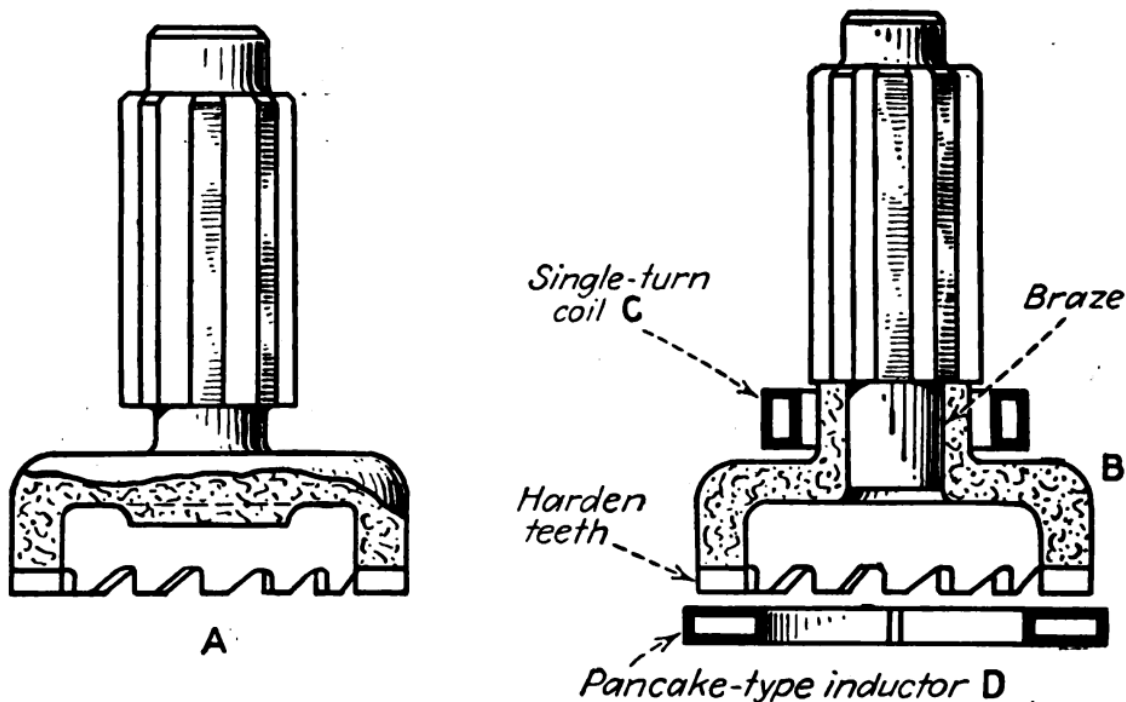
Fig. 236.—An example of a two-piece assembly which has substituted a single-piece design. Induction heating is used for silver brazing the two parts together, as well as for hardening the clutch teeth.

hardened areas on which needle bearings operate. These surfaces are hardened simultaneously to 61 to 63 Rockwell C by means of a series-type induction-heating coil.
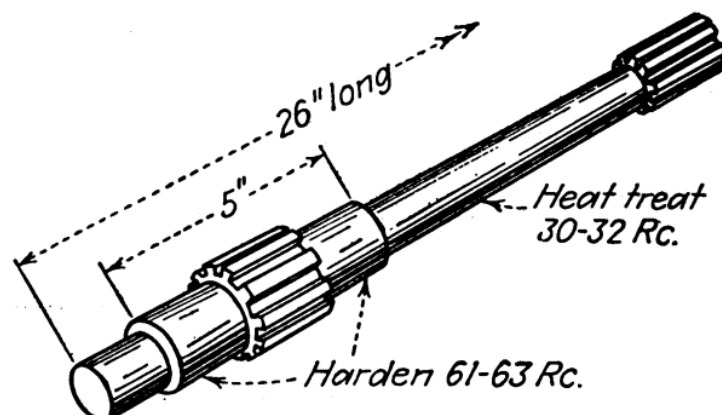
Fig. 237.—This shaft requires two hardened journals on which needle bearings operate. Ordinarily, the entire end would have to be heated, with the possibility of distortion and the need of a strengthening operation. Induction hardening has simplified the necessary processing.

Before the application of induction hardening it was necessary to heat the entire end of the shaft which, likewise, was quenched and drawn. This caused the surface of the heated areas to

become badly scaled and usually there was a slight amount of deformation causing a rather difficult straightening operation because of the short distance in which the warpage took place. With induction hardening, however, heat is localized to the surface requiring hardening, thus entirely eliminating warpage. Also, the hardened surfaces are produced practically free of scale, so that with a minor buffing or cleaning operation, they can be used as bearing surfaces. On other parts of this type it may be advisable to grind the journals after hardening, in which case a very small allowance has to be made.

High-frequency induction heating has many uses in all types of industrial plants and its application undoubtedly will play an important part in our future manufacture. As in the case of any new process, it is necessary to follow through with certain procedures, such as the designing principles herewith described, in order to attain its full benefits—economical heat, quickly applied, with extreme uniformity.

CHAPTER IX

DIELECTRIC HEATING

Another form of high-frequency heating is that known as dielectric heating, which is applied to materials that normally are nonconductors of electricity, and usually nonconductors of heat The process of dielectric heating differs from induction heating in that a much higher frequency is required. The frequencies usually applied for the heating of metals have little or no effect on dielectric materials, and vice versa.

Induction heating provides for the transfer of eddy currents into a material which must be electrically conductive. The surrounding coil, which carries the high-frequency current, forms the primary cf what may be termed a transformer, while the metal part to be heated forms the secondary. This type of heating is used most to heat a localized surface of a metal part. The depth of heat penetration may vary from a rather thin skin to a relatively deep area, as may be determined by the frequency used and the time cycle employed.

With dielectric electrostatic heating, as it often is called, the material to be heated is placed between two electrodes, usually spaced the same distance apart at all points. Energy is applied to the plates and heat is produced simultaneously throughout the area of the charge, usually at a rather rapid rate.

Dielectric heating is used in the pre-curing of practically all types of plastics, cellulose fibers, and celluloid. Its field also covers the heating and treatment of rubber, wood, paper, ceramics, cork, textiles, and many other dielectric materials.

Cause of Heating. All materials are made of molecules which, when rubbed together, create a certain amount of friction that produces heat. The more intense the friction, the more pronounced the heat. A small strand of wire, for example, twisted rapidly back and forth will create heat where it is twisted, because of the molecular disturbance at that point.

When an alternating current is subjected to a dielectric material, the molecules try to align themselves to the alternating

field, rubbing themselves together with each cycle, or reversal of polarity, and a pronounced molecular friction is set up. When the alternating field is reversed several million times a second, a considerable amount of heat is naturally created because of the molecular friction that takes place. This, briefly, is the principle involved in dielectric heating.

Materials normally considered insulators, often referred to as dielectrics, will absorb some electric energy when placed between electrodes of a high-frequency field. If a material were an absolute insulator, heating would be difficult, but most materials have a sufficiently high loss factor to be heated by high-frequency currents. From this it will be seen that the loss factor bears a direct relation to heating results; the lower the loss factor the slower the generation of heat, and the higher this factor the more pronounced the heating effect.

Nonmetallic materials are heated by placing them between two electrodes. The material forms the dielectric of a condenser and therefore the dielectric losses cause the material to heat. The power factor is extremely important, because on it will depend the possibility of heating a material.

To induce ordinary current to flow through nonconducting materials would be impossible unless the resistance to the flow of current could be reduced. However, by increasing the frequency of the current it is possible to cause the passage of current through nonconducting materials. The amount of heat produced, then, will depend on the physical characteristics of the material rather than its electrical properties.

A typical high-frequency generator for dielectric heating is illustrated in Fig. 238. This generator has an output rating of $3\frac{1}{2}$ kw. and can be operated at various frequencies of 10 to 50 megacycles. For most woods and plastic materials, heat can be produced satisfactorily at frequencies of 5 to 20 megacycles. With other materials having a lower power factor, it is necessary to apply higher frequencies ranging from 20 to 50 megacycles, or even 100 megacycles or more.

The internal construction of the generator is illustrated in Fig. 239. The lower section of the unit houses the power supply, whereas in the upper section is located the oscillatory portion of the circuit.

High-frequency generators for dielectric heating are available in various sizes from as low as ½ kw. to 200 kw. and for special applications may even exceed this maximum power output.

Vacuum-tube oscillators for dielectric heating utilize three-element radio tubes. Two current sources are used; one is for
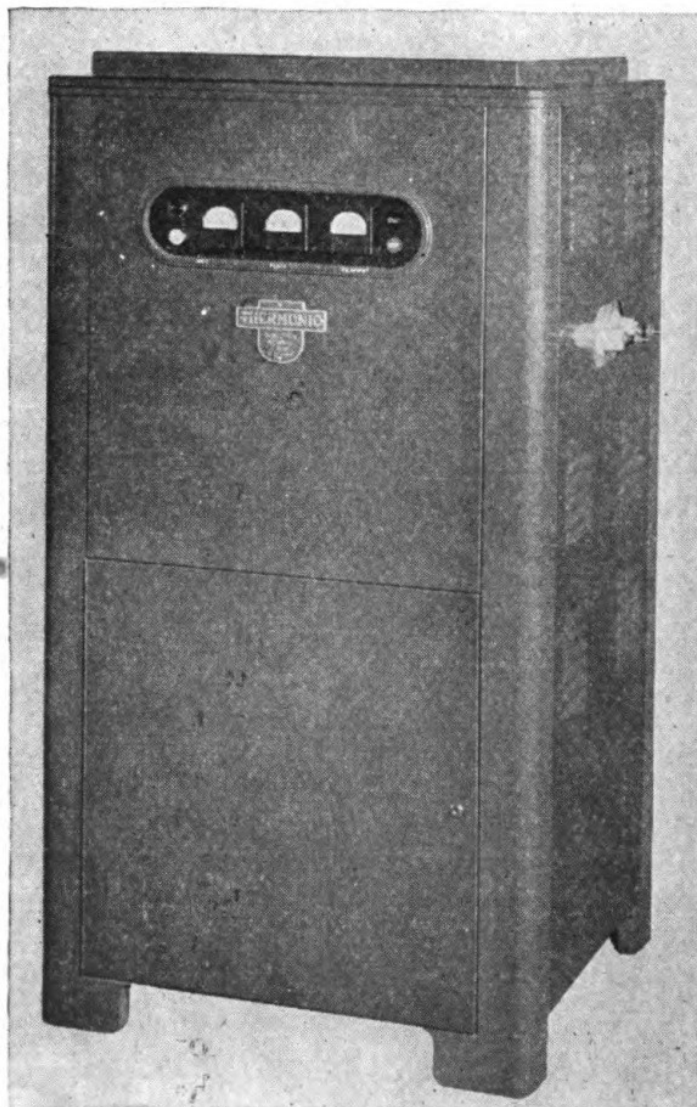
FIG. 238.—Dielectric heating units are made in various sizes. The unit shown above has an output rate of 200 B.t.u. per min., and operates at various frequencies up to 50 megacycles. (*Courtesy of Induction Heating Corp.*)

the filament of the tubes, usually ranging from 5 to 22.5 volts, and the other is a high-voltage direct current, which may vary from 2,000 to 20,000 volts, depending on the size of the generator. A simplified diagram of a single-phase dielectric heating circuit is illustrated in Fig. 240.

The alternating-current input power is brought in to a center-tapped transformer, where the voltage is stepped up as required,

usually to about 10,000 volts. The output current of the transformer is rectified in order to supply direct current to the two-tube push-pull oscillator. The oscillator then generates current at a frequency of 5 to 50 megacycles, or higher as may be required. Power is taken from the circuit to the electrodes. The material to be heated is placed between these electrodes, which in turn
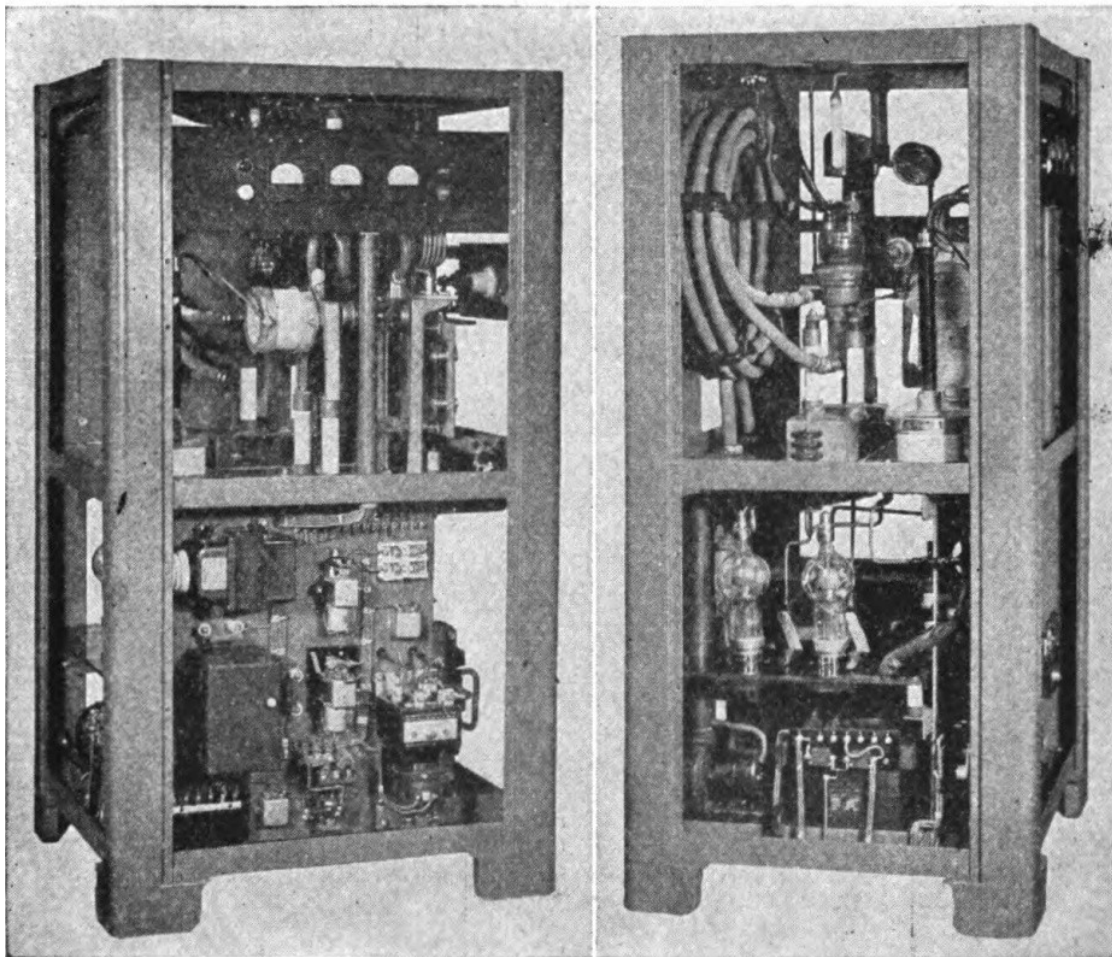
FIG. 239.—Internal assembly views of a dielectric heating unit, showing the power supply section located below, and the oscillating section above. (*Courtesy of Induction Heating Corp.*)

are connected into the tank circuit by taps on the tank-circuit coil.

Comparative Heating Methods. In using hot plates, as illustrated at the left in Fig. 241, heat must be conducted from the exterior to the interior, and the time required may run into several minutes. Heating depends entirely on conduction since heating begins on the outside, nearest to the source of heat, and moves inward by thermal conduction. With this method the material does not become heated uniformly. Assuming a tem-

perature of 225°F. were wanted, the outside may attain this heat but the inside may reach only 150 to 220°F., depending on the nature of the material and the duration of heating time.

Dielectric heat, obtained as shown at the right, is produced in the material itself and is uniform from the inside to the outside
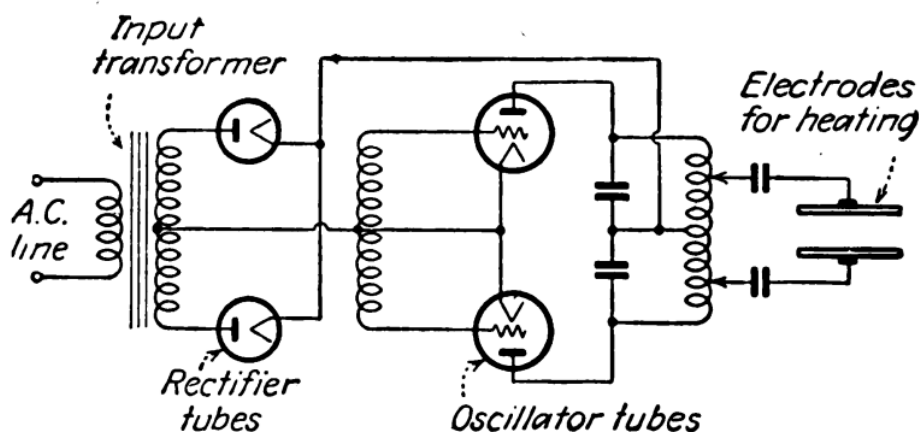
Fig. 240.—A typical circuit for a dielectric heating unit. The line voltage is stepped up by means of an input transformer, then rectified to supply direct current to the oscillator tubes.

of the material. Whatever variation may take place is due to radiation and conduction losses at the surface which may possibly cause a slight outward flow of heat.

Contrasted with hot-plate heating, in the dielectric method a temperature of 225°F. can be obtained throughout the entire
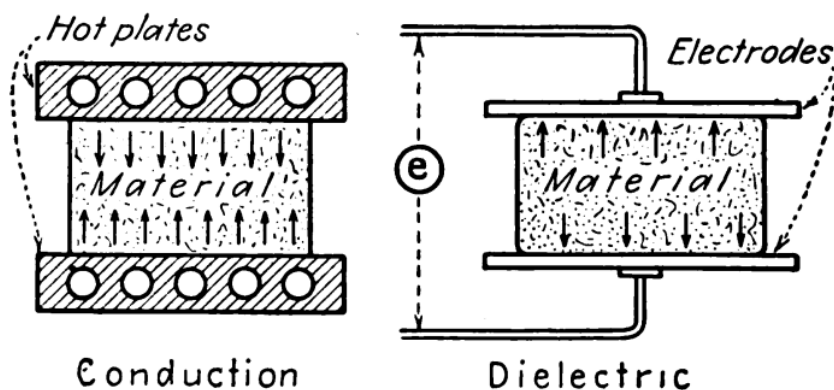
Fig. 241.—This diagram shows the comparison between hot-plate heating and high-frequency electrodes. With hot plates, heat depends entirely upon conduction and uniform temperatures are rarely obtained. With dielectric heat, the temperature rise will be uniform throughout the material being heated.

area of the material. Heating will be uniform and the temperature rise will be the same throughout the thickness.

Heating Plastic Preforms. One of the outstanding applications for dielectric heating is in the precuring of plastics, as required for transfer molding. This is carried out by first pre-

forming the plastic material to a flat shape, then placing it between the electrostatic electrodes for the precuring or preheating cycle, after which the preform is placed in the mold and cured. From this it will be seen that dielectric heating is pri-
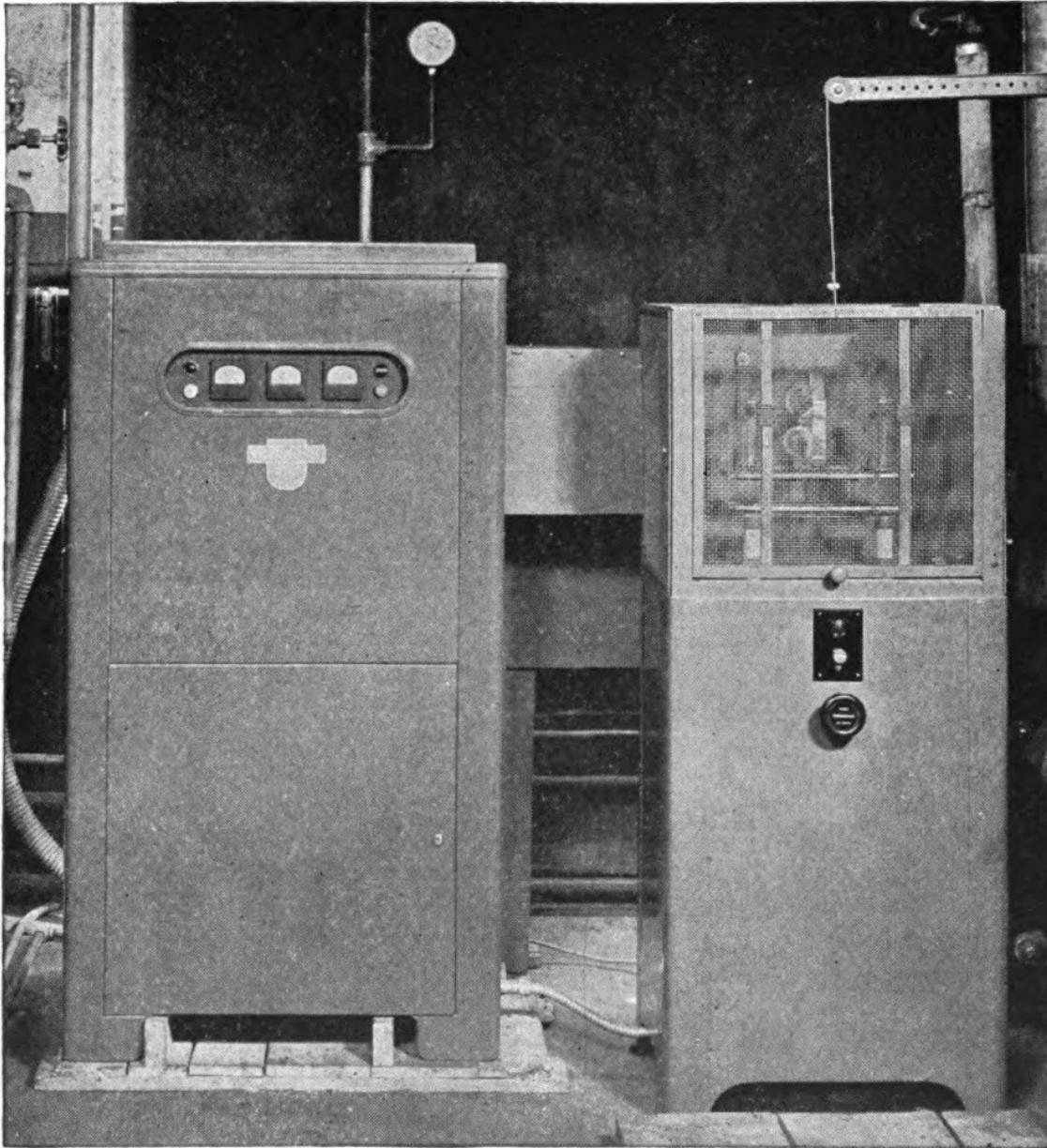
FIG. 242.—A typical high-frequency dielectric heating installation used in transfer molding. The generator is shown at the left and the electrode heater at the right. (*Courtesy of Induction Heating Corp.*)

marily for the preheating of the preform prior to molding. Since a uniform heat is produced throughout the preform, marked improvements in the molding properties are obtained.

As a comparison with former methods, let us assume that a preform was heated by conduction and that 6 min. were required to preheat it to 250°F. The molding time may then require

6 min. to cure the form completely. With dielectric heating the preform may require only from 40 sec. to 1 min. for the preheating cycle, and since a uniform temperature has been produced throughout its area the molding time may be only 3 min. This reduction in molding time is the result of improved flow properties in dielectric heating.

Due to the high voltage across the electrodes of a dielectric heating unit, it is necessary to provide a screen or shielding
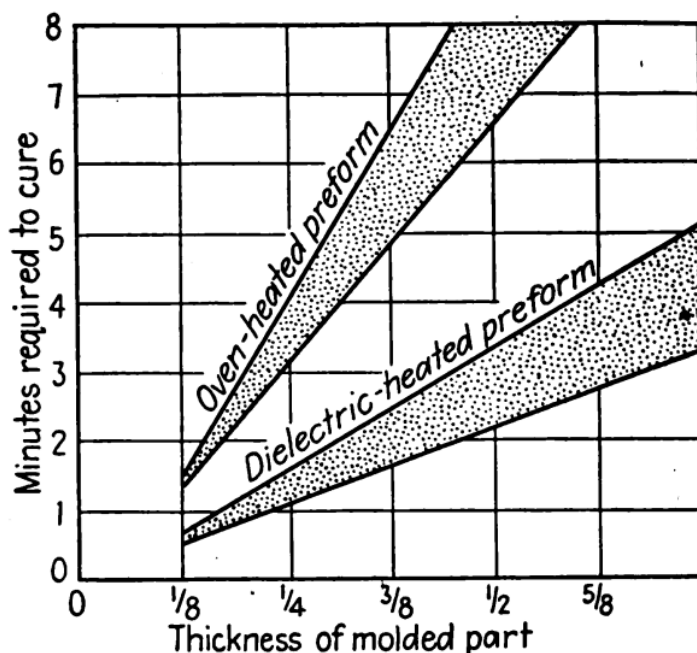
FIG. 243.—This chart shows the comparison of the time required to heat plastic preforms by means of oven heating, with that required for dielectric heating.

around the plates as a precaution against injury to the operator. Such a unit may be seen in Fig. 242, at the right-hand side of a high-frequency generator. The lower electrode is fixed and the upper one is adjustable to the thickness of the plastic preform. When the front door of the heating unit is elevated the upper electrode is automatically raised slightly to facilitate the removal and the insertion of the preforms. Also connected with the movement of the door is a limit switch which breaks the circuit when the door is opened and automatically closes the circuit when the door is lowered or closed. After the proper curing time has been established for a given preform the cycle is controlled by a timer, so that repeated heats may be uniform. Starting of the cycle is by means of the push button, shown at the front.

In Fig. 243 is shown a chart representing comparative molding time for thermosetting plastic sections varying in thickness, when

the preforms are heated by oven or by the dielectric method. The preheating and molding times will vary, depending upon the type of plastic and the source of high-frequency power, but substantial time reductions are made possible, sometimes exceeding 50 per cent of former curing requirements.

Dielectric heating for plastics offers other indirect savings. One is the fact that thicker sections can be molded, with less chance of uncured sections or the formation of open seams. There also is the possibility of reducing the molding pressure as much as one-third, so that press costs and maintenance requirements are lessened. Likewise, available presses can handle larger molds, or a press of a given size will accommodate a wider range of molds than was possible before.

Power Requirements. In heating plastics having an average specific heat of 0.4 to 0.5, it usually requires about 2 kw. to heat 1 lb. in 1 min. to 300°F. The formula used for dielectric heating is similar to that applied to induction heating in that a certain mass of material having a given specific heat must be heated to a given temperature, and that so many B.t.u. will be required. The formula would be

$$W \times S \times T = \text{B.t.u.}$$

where W = the weight of material.

S = the specific heat.

T = the temperature rise desired.

This formula, of course, does not take into consideration the voltage and frequency, but as a rule will serve as a quick means of determining the approximate power required to heat dielectrics. With this can be included

$$1 \text{ kw. output} = \frac{3413 \text{ B.t.u.}}{60} = 56.71 \text{ B.t.u. per min.}$$

Assuming that a piece of preformed plastic weighing 2½ lb. requires heating to 250°F. and that the material has a coefficient of specific heat of 0.4, we would have

$$2.5 \times 0.4 \times 250 - 250 \text{ B.t.u.}$$

If a generator with an output capacity of 5 kw. were used it would produce

$$56.7 \times 5 = 283.5 \text{ B.t.u. per min.}$$

as its available power, from which the heating time for the 2½-lb.

mass would be

$$\frac{283.5}{250} = 0.88 \text{ min.}$$

Where a more accurate calculation is required to allow for such
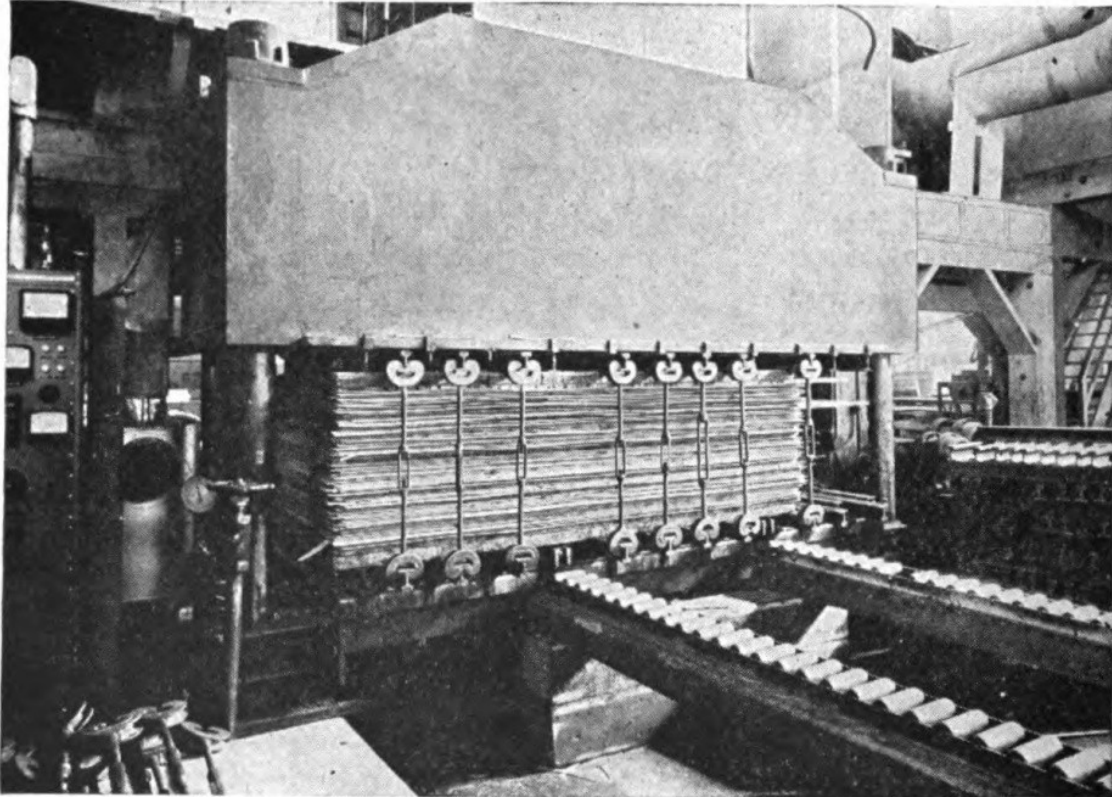
Fig. 244.—This illustration shows the former method required to prepare plywood for drying. After the charge is pressed together and clamped, it is transferred to a drying room. (*Courtesy of The Girdler Corp.*)

factors as the frequency, thickness of the part, and its loss factor, the following basic formula can be applied:

$$H = CFL\frac{E^2}{T}$$

where H = heat per unit volume.

C = dielectric constant.

F = frequency.

L = loss factor.

E = voltage.

T = thickness of part.

The coefficient of the specific heat of a material is expressed by the number of B.t.u. required to raise 1 lb. of that material 1°F. Material having a specific heat of 0.5, for example, would mean that it would take 2 B.t.u. to raise 1 lb. of material 1°F. The specific heat of the materials is based on the standard of

1.0 which is applied to water, which means that it takes 1 B.t.u. to raise 1 lb. of water 1°F.

High-frequency Heating of Wood. Another outstanding use of dielectric heating is in the joining of plywood, or laminated sections which require an elevated temperature to, dry the adhesive bond. Representative of this application is the drying of plywood sheets. In Fig. 244 is illustrated an existing method
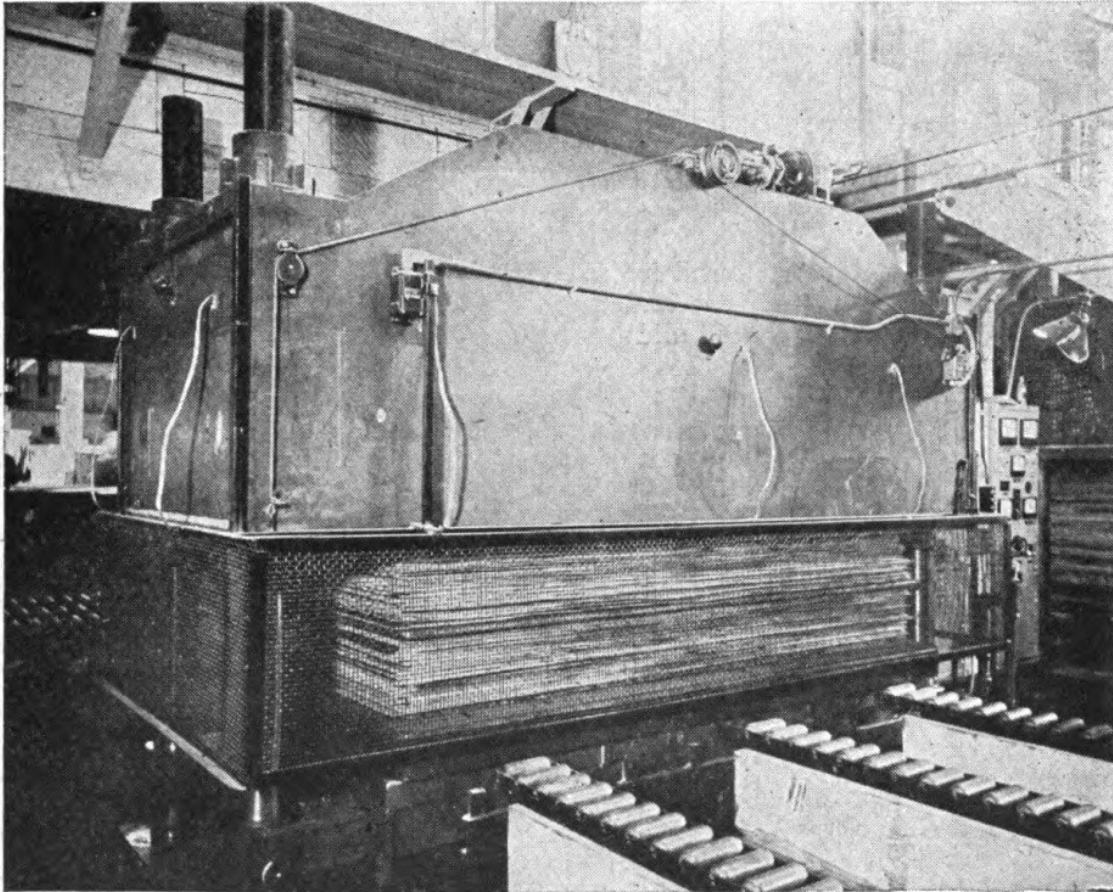
FIG. 245.—With dielectric heating, plywood can·be dried in the press in a comparatively short time, so that drying rooms and storage facilities are eliminated. (*Courtesy of The Girdler Corp.*)

used for preparing plywood for drying. Here several sheets are placed in a press, squeezed together by hydraulic pressure, and then held in tension by a series of clamps attached around the edges, as may be seen. The charge then is transferred to a drying room in which from 10 to 12 hr., or even more, are required for drying to assure a suitable bond. With this process a considerable storage space is required.

The application of high-frequency heat to plywood, however, is such as might require only a few minutes to dry a similar quantity of plywood, and in Fig. 245 is shown such an installa-

tion. The plywood sheets are placed within a hydraulic press, and within a few minutes the temperature throughout the mass
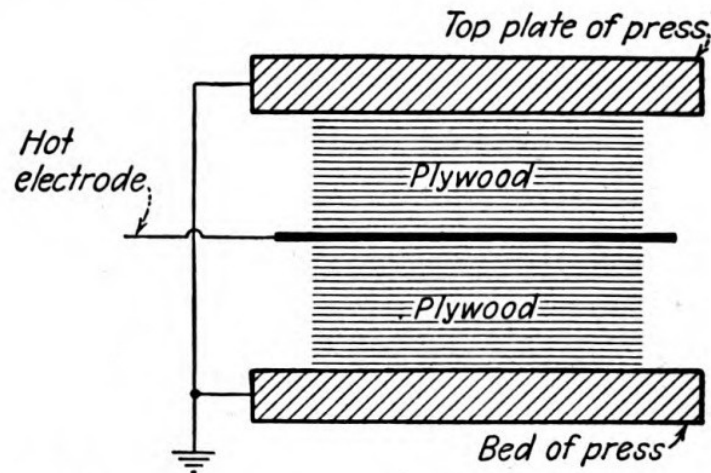
FIG. 246.—The method used for applying high-frequency heat to plywood is shown above. The top plate and base of press are connected to the ground, and a hot electrode is located midway between the panels being glued.
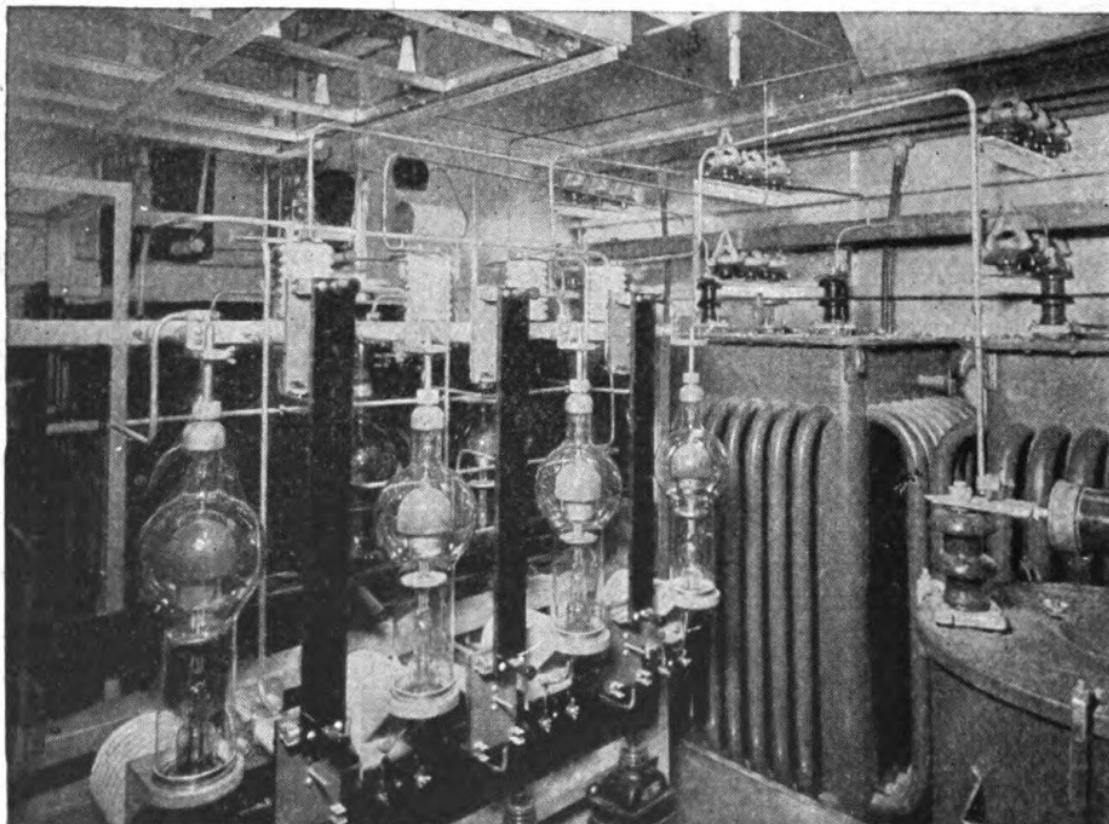
FIG. 247.—An interior view of a large dielectric heating generator, which is used for the drying of plywood. (*Courtesy of The Girdler Corp.*)

is raised 200 to 250°F., as required, after which the plywood sections are ready for finishing operations. No storage is required and usually the charge can be cured in about the same time as was formerly needed to apply the holding clamps used

in the other method. In applying high-frequency heat to ply-wood the ground lead is connected to the top plate and the base of the press, as illustrated in Fig. 246, then a center electrode is applied midway between the plywood sheets. Sometimes a series of plates are used for heating, although the electrode connection is made only to the center plate. These plates do not have any effect on the heating process.

The interior construction of a large high-frequency generator is illustrated in Fig. 247. The input transformer used to raise the voltage is shown to the right in the rear. Several of the tubes used in the circuit are shown in the foreground. The tank condenser is shown at the extreme right.

Advantages of Dielectric Heating. The application of high-frequency heat to dielectrics has many advantages. Basically, a more uniform heat is distributed through the part being treated; heat is applied at an exceptionally fast rate so that the output may be increased; and uniformity of heat can be produced without variation, thus reducing spoilage. Since dielectric heat can be applied to such a variety of nonmetallic materials of different structures and compositions, various other advantages are also obtained. These are:

Often a better quality of product is the result of uniform heating, which can be obtained in no other way.

Processes of manufacture can be modified in many cases, with less handling and fewer subsequent operations.

Faster heating or drying usually reduces floor space and, as a rule, reduces inventory which might otherwise be tied up due to slower heating or drying processes.

No delay in obtaining instant heat, as compared with other methods where drying ovens or furnaces may require considerable time to reach a given or desired temperature.

Heat may be stopped instantaneously, which in some cases may prevent overheating and possible spoilage of products.

Dielectric heat can often be used to obtain a desired chemical reaction.

Dielectric Dehydration. Another form of high-frequency generator with an output-power rating of 3 kw. is illustrated in Fig. 248. At the right of the unit may be seen the electrodes, which are made adjustable to various thicknesses of material.

In use, however, the electrodes require shielding as a protection to the operator.   This unit operates at a frequency of 15 megacycles.

Among the many uses for dielectric generators of this type is the dehydration of food.   In Fig. 249 is shown a test setup for
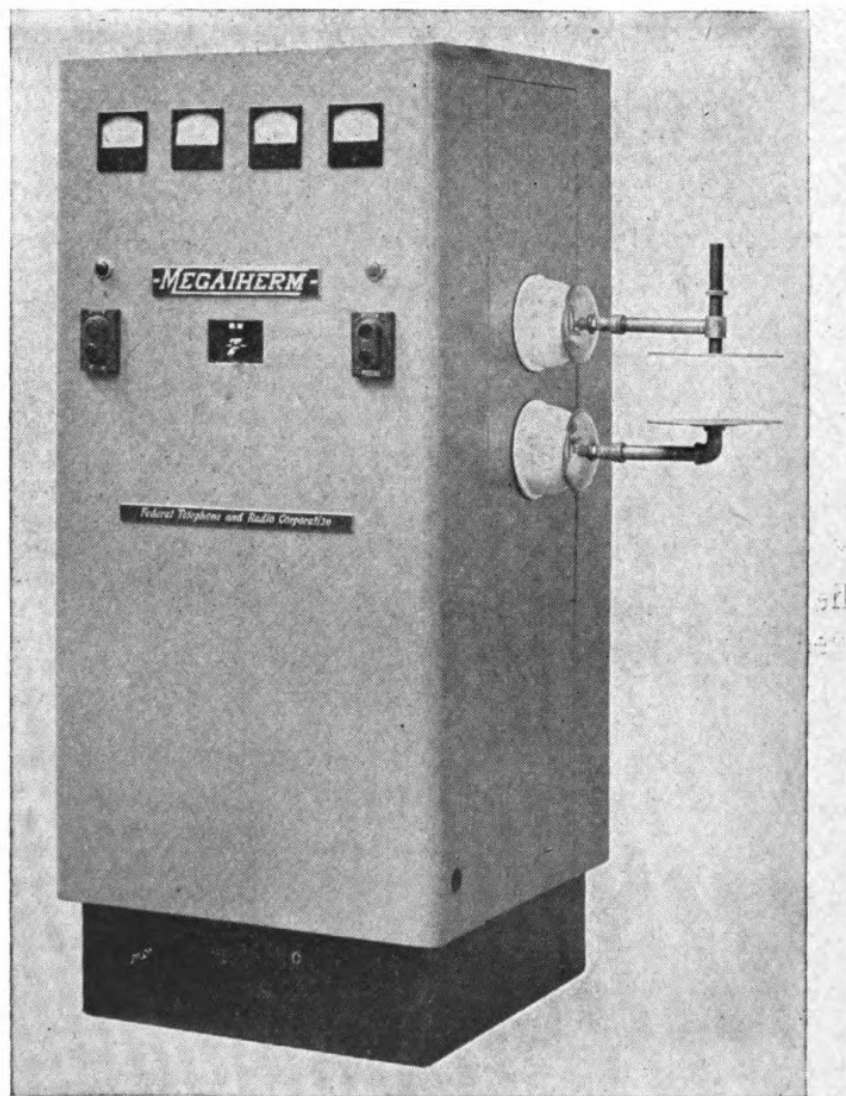
Fig. 248.—A small dielectric heating unit provided with adjustable elec. This generator has an output rating of 3 kw. and operates at a frequency o. megacycles.   (*Courtesy of Federal Telephone & Radio Corp.*)

this purpose.   The samples, previously compressed at a 500-lb. pressure, are placed between electrodes over which a bell jar is placed to provide a vacuum.   Temperatures of 120 to 150°F., depending on the type of food being dehydrated, are used and moisture content can be reduced to 1 per cent or less without burning or affecting the outside surface.   The process is relatively fast and the cost of operation comparatively low, or less than 100 watts per lb.

No attempt has been made to cover the use of dielectric heat in great detail. The references given, however, are more for the purpose of showing the difference between induction heating and dielectric heating. In many respects the equipment used for both methods is similar in construction, although the applications
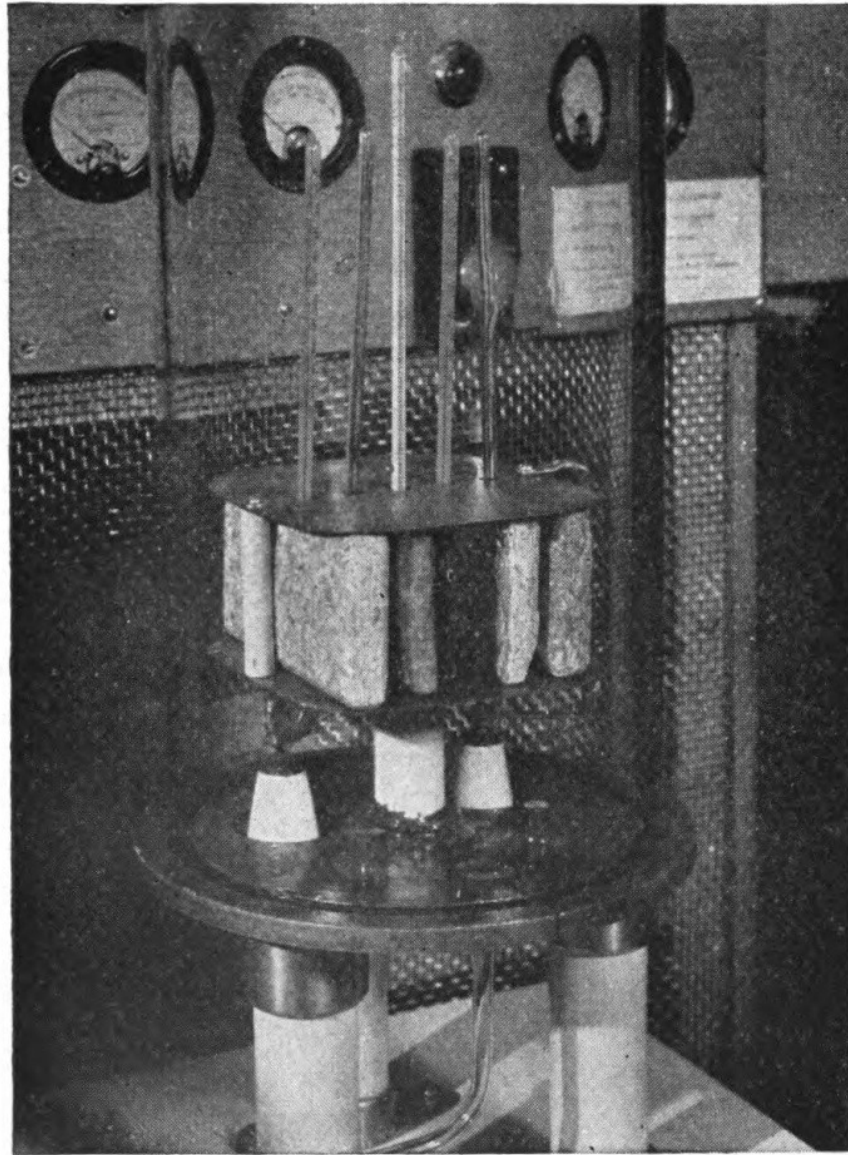
FIG. 249.—A laboratory setup using a dielectric generator for the dehydration of food. Various temperatures can be obtained, so that the moisture content can be reduced to 1 per cent or less. (*Courtesy of Federal Telephone & Radio Corp.*)

are entirely different and have little similarity. The use of induction heating, which has been the primary purpose of this book, is suited to the heating of metals, whereas dielectric heating primarily is intended for nonconductors. Occasionally there might be a choice of either of these heating methods, but such cases will be rare since each method has its own distinctive field.

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